Overgrid: A Fully Distributed Demand Response Architecture Based on Overlay Networks

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***Abstract*—In this paper, we present *Overgrid*, a fully distributed peer-to-peer (P2P) architecture designed to automatically control and implement distributed demand response (DR) schemes in a community of smart buildings with energy generation and storage capabilities. As overlay networks in communications establish logical links between peers regardless of the physical topology of the network, the Overgrid is able to apply some power balance criteria to its system of buildings, as they belong to a virtual microgrid, regardless of their physical location. We exploit an innovative distributed algorithm, called flow updating, for monitoring the power consumption of the buildings and the number of nodes in the network, proving its applicability in an Overgrid scenario with realistic power profiles and networks of up to 10 000 buildings. To quantify the energy balance capability of Overgrid, we first study the energy characteristics of several types of buildings in our university campus and in an industrial site to accurately provide some reference buildings models. Then, we classify the amount of "flexible" energy consumption, i.e., the quota that could be potentially exploited for DR programs. Finally, we validate Overgrid emulating a real P2P network of smart buildings behaving according to our reference models. The experimental results prove the feasibility of our approach.**

***Note to Practitioners*—In this paper, we propose a scalable solution for supporting distributed load control in a community of smart buildings, whose deployment requires minimal communication overhead and no dedicated investments for the control network. The control system, called Overgrid, is implemented over an unstructured peer-to-peer (P2P) overlay based on gossiping, a commonly used paradigm allowing a strong and scalable information diffusion (fault tolerant) across the network, totally decentralized, and with low network overhead. Overgrid creates the P2P network over the electrical grid (thus the name Overgrid), in which the management of electrical loads is carried out by the nodes participating in the network through innovative distributed algorithms. We exploit a one-year study of power consumption traces in a reference industrial site and simulation-based traces for residential buildings, in order to test the effectiveness of our solution in realistic scenarios.**

***Index Terms*—Gossiping, overlay networks, peer-to-peer (P2P), smart grid.**

I. INTRODUCTION

TRADITIONALLY, energy demand was much more variable and less controllable than supply, so energy balance was achieved by adapting dynamically generation levels to match consumption. Now, the increasing penetration of unpredictable renewable energy has radically changed the situation. Wind and solar generation experiences intermittency, a combination of noncontrollable variability and partial unpredictability, and depends on resources that are location dependent [1]. It follows that the integration of these energy sources into electric grids requires an increment of the power system flexibility, which can be achieved both by considering efficient integration of energy resources (widely studied since 1997 [2]) and the control of location-dependent power demand. Two common approaches for controlling the power demand are commonly classified as *reactive* and *dispatchable* demand response (DR). The former refers to the possibility of end users changing their normal consumption patterns in response to a dynamic price signal; the latter (also called load control) refers to the possibility of the energy utility or third party entities of directly switching some specific user appliances off during peak demand periods or tuning their operation conditions for reducing the power demand.

In this paper, we deal with load control mechanisms working on the aggregation of a number of smart buildings, i.e., buildings equipped with Internet connectivity and a local communication network for the control of electric smart appliances. Indeed, most of the current load control programs work on large industrial loads or domestic thermostatic loads. Large industrial loads have a significant and well characterized power demand and can be disconnected according to prearranged agreements between the energy utility and the customer with very simple decisions and control networks [3]. Domestic thermostatic loads, such as air conditioners and heating systems, allow a fine-tuning regulation of power demand [4], but require to involve a very large number of customers, thus making the control algorithms more complex [5]. The aggregation of smart buildings represents an intermediate solution between the extreme case of large industrial customers or independent residential customers, and a good tradeoff between the power demand flexibility (e.g., maximum amount of power shift that can be achieved) and complexity of the control system.

The reference smart buildings considered in our study are four buildings of our campus, whose consumption patterns have been characterized and modeled as detailed in Section IV, and an industrial research center that works in proximity of the campus. We propose a completely distributed solution

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for supporting the creation, maintenance, and operation of a community of buildings, whose power demand is similar to our reference buildings, which jointly participate to the load control program. The solution is based on two main aspects: 1) using Internet and a peer-to-peer (P2P) communication model for creating the control network between the buildings, without any dedicated investment for servers and communication infrastructures[1] and 2) using gossip-based protocols for estimating the aggregate power demand of the community and responding to the load modulation requests, as detailed in Section III. We call the community of buildings participating to the load control program an *Overgrid*. Indeed, in case smart buildings are also equipped with local generation and storage systems, the system as a whole can act as a virtual microgrid, which is not able to work independently from the electric grid, but can be independent in terms of overall energy balance.

In the implementation of Overgrid, we make use of an innovative algorithm, namely, flow updating [6], for distributedly monitoring the state of the P2P network. To prove the feasibility of our approach, we emulated the behavior of an Overgrid by setting up a virtual network of buildings whose power demand was simulated according to our reference building models. We analyzed the performance of the Overgrid gossip protocol for aggregating the building power demand and responding to different power reduction signals, as the connectivity degree of the network varies, demonstrating the applicability of flow updating with realistic power profiles and distributed networks of up to 10 000 buildings. Our results show that the system is quite robust to topological changes and message losses, the adaption times are compatible with the typical times expected for DR mechanisms, and generalization to systems at different (larger or smaller) scales is possible. Therefore, we argue that our solution can be of practical interest in many emerging scenarios, in which consumers can be aggregated without the need of third party operators.

II. RELATED WORK

A. Communication Infrastructures for Load Control

Load control can work at different levels in the energy grid, for attenuating voltage regulation problems (primary level), enforcing desired consumption profiles (secondary/tertiary level), affecting the electricity market (price zone level), thus achieving the heterogeneous goals of improving the grid reliability [7], or performing operation savings [8]. Different players can be involved into the program: the energy supplier can interact with the distribution system operators (DSOs) and/or with novel intermediate figures called load aggregators [9], before reaching the final consumers and enforcing a change in their power demand. While the involvement of the DSO has some obvious implications for the maintenance of the electric grid, the presence of the load aggregator is envisioned for introducing an intermediary, which simplifies the interaction with large numbers of consumers. Moreover, the aggregator can collect information on user profiles and willingness to respond to control actions for dispatching the controlled loads as a response of the higher level commands. In all the cases, the control program requires an underlying communication infrastructure that allows the necessary information exchange between the different players (energy utility, DSO, industrial or residential users, load aggregators, etc.) and domains [low-voltage (LV), medium-voltage, or high-voltage (HV) grid segments, price zone, etc.] involved in the program.

Direct load control programs have been activated in pilot projects for both residential and industrial customers. For residential customers, some utilities also offer commercial services [10] based on the deployment of radio-controlled switches on air-conditioning units or electric water heaters at the customers' premises. For industrial customers, the control mechanisms are very simple and often based on voice dispatch (i.e., a telephone network) [3]. Conversely, for large-scale deployments working on residential users [11], alternative communication infrastructures have to be considered. In case the DSO is involved into the control program, it is possible to utilize the advanced metering infrastructure, mainly based on PLC (where possible) and GPRS technologies, for transporting load control signals [12]. Conversely, Internet connections available in most households may enable more flexible programs managed by third parties [13]. In this case, the supplier can communicate to the load aggregator requesting not to exceed a maximum absorbed power during a specific time interval [14] or to exceed a given power demand with a probability smaller than a desired bound [15].

B. Service Architecture

Most of the current load control programs are centralized: control decisions are taken by the DSO, energy supplier, or load aggregator on the basis of dynamic programming optimization [5], fuzzy logic-based decisions [16], or other profit maximization schemes [17], and enforced to the customers. Even in the case of decentralized dispatch based on price signals that affect the user decisions [18] (without providing any guarantee), price signals are decided at a central level. In other words, load control is mostly based on a traditional client–server service architecture, in which a global server maintains the links with each industrial or residential customer for dispatching control/price messages and collecting monitoring data.

For large-scale load control working on residential users, scalability and reliability could be critical issues because it is required to interact with large number of users and communication links. A different service architecture based on P2P communications could respond to these requirements better than client-service architectures, by explicitly dealing with the potential increment of the communication delays [19]. In P2P networks, all the nodes have equivalent functionalities and keep contacts with a subset of nodes, called neighbors, rather than communicating with a single server. These features make P2P networks very effective to create large-scale distributed applications over the Internet, such as on-demand distribution of video content and video streaming [20]. The possibility to exploit P2P networks in smart grid applications has been

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[1] We assume the Internet connection to be already available for the participating peers and that a gateway or local "energy manager" runs the proposed algorithms in each building.

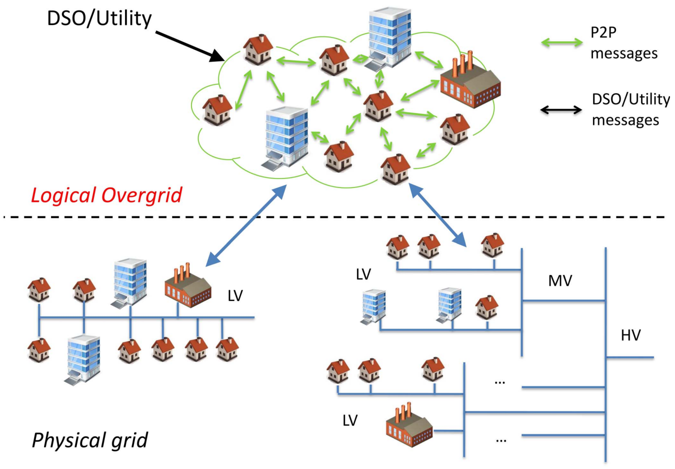

Fig. 1. Reference scenario for the Overgrid.

discussed mainly for secondary and tertiary control on a microgrid [21], or for disseminating and aggregating information in the metering infrastructure [22], [23]. In our work, we propose a similar approach to the load control problem, by enabling the creation of a completely distributed community of smart buildings, which participate to the program without intermediaries.

III. OVERGRID CONCEPT

The key idea in Overgrid is the generalization of the concept of microgrid, from a *localized system* of loads and energy resources, which can be disconnected from the main grid, to a *virtual community* of smart buildings equipped with controllable loads, local generators, and storage systems, which cannot work in isolation, but can support a desired energy balance with the main grid.

Fig. 1 represents the Overgrid concept; by enlightening, that group of buildings (also called nodes) participating to the Overgrid can be mapped to different placements on the energy grid: on the same LV segment, as shown in the left case, in different LV segments in the same HV segment, as shown in the right case, or even in independent distribution networks in the same price zone. Indeed, multiple criteria can be considered for clustering the smart buildings in an Overgrid, such as physical proximity in an edge part of the distribution network, complementary power demands that allow exhibiting a stable aggregated demand, similar equipment for energy storage or load control that allows supporting homogeneous control actions, and types of contracts with the energy utility. Regardless of the specific clustering criterion, which is out of the scope of this paper, the goal of the community is trying to guarantee a desired power balance with the rest of the grid, according to a dynamic signal $\mathrm{DR}(t)$ provided by the DSO or energy utility. For a community of n nodes, being $\mathrm{load}_i(t)$ the power demand of node i at time t (which can be negative for taking into account local generation systems), the instantaneous balance can be expressed as $\sum_{i=1}^{n} \mathrm{load}_i(t) = \mathrm{DR}(t)$.

The dynamic constraint $\mathrm{DR}(t)$ can be equal to zero for imposing that the Overgrid is energetically independent from the rest of the grid, or lower than zero for imposing that the Overgrid provides power to the rest of the grid. Note that the power demand of each building is measured by sampling the real consumption at regular time intervals T (typically of 5 min), and similarly the signal constraint is a piecewise constant function that imposes the same constraint during a time interval of kT (typically 15 min, i.e., $3 \cdot T$). It follows that the previous balance condition can be considered as a discrete-time condition, if we consider both the power demand measurements and the power constraints as time series with a common sampling interval T.

To achieve the desired power balance, we consider a completely distributed service architecture, based on P2P communications. A distributed control protocol allows each node to estimate the aggregated power demand and constraint of the Overgrid in a given time interval, without inquiring any centralized server, and to implement a local load control in order to meet the desired balance.

A. Architecture Overview

We assume that each smart building joining the Overgrid is equipped with an Internet connection for exchanging control messages with the other nodes of the community. Moreover, a local communication network (based on WiFi, ZigBee, power line, etc.) is available for controlling the electric appliances and/or the production and storage systems, with a response time comparable with the Internet latency (in general, up to few seconds). The specification of the technology for supporting the *local* communication network and load control is out of the scope of this paper.

On top of the physical communication network between the nodes, Overgrid implements an unstructured P2P overlay network, where nodes do not have *a priori* knowledge of the topology and communicate with the neighbors by means of gossip protocols [24]. Gossip protocol scalability comes from the fact that each node is in communication with a subset of other nodes (typically much smaller than the entire size of the network), which represents the neighbors of the node. This architecture is intrinsically fault tolerant, totally decentralized, and with low network overhead. No dedicated server or other centralized resources are required for creating the "community" of smart buildings.

The Overgrid gossip protocol works according to a generic push–pull structure. Each node executes a main loop for sending, at regular time intervals, a message containing its local state to a random neighbor (*active thread*). Upon the reception of a message, the neighbor replies with another message, sending back its local state to the node starting the message exchange (*passive thread*). Both the nodes involved in the message exchange update their local state as a function of the information fields transmitted by the peer node. Finally, each node runs independently several distributed functions to maintain the connectivity of the P2P network, for disseminating information to the neighbors, for data aggregation and estimation of network-wide parameters and distributed load control.

B. Distributed Functions

The gossip protocol is responsible of three different aspects: 1) building and maintaining the network topology; 2) disseminating information about $\mathrm{DR}(kT)$ among the Overgrid nodes; and 3) aggregating local data for estimating the overall power demand $\sum_i \mathrm{load}_i(kT)$. Three independent local state components are used for managing the information relevant to these aspects. Gossip messages can include one or more of these state components, while peer sampling is always based on random selection. On the basis of the local estimate of the total power demand and power constraint, each node has finally to perform a load control scheme.

1) Topology Management: The local state used for building and maintaining of the P2P network is given by the list of neighbor nodes and by the relevant activity indicators (also called *heartbeat*). Messages transporting this local state are generated at fixed time intervals and are usually independent from the messages used for disseminating or aggregating data in the network. The heartbeat of a given neighbor is increased of one unit when a message (of any type) is received by that neighbor, while the neighbor list is updated when a node receives a message from a new neighbor or when a neighbor is inactive for a long time interval. When a node is activated for the first time, a local configuration file provides an initial neighbor list that contains at least one neighbor node. The list is updated after the node exchanges the first message with a neighbor, by learning about the neighbors of the neighbor.

2) Information Dissemination: Information dissemination is used for notifying the power demand constraint, which is received at regular time intervals by a random node of the P2P network, to all the nodes. The local state is given by last received power constraint and by the timestamp indicating when the data have been generated. Nodes update the local state to a new value when they receive a message with a more recent timestamp. This requires that a common reference time is available at each node. Because the load control dynamics considered in our work evolve at scales of the order of several minutes (typically, 15 min), such a synchronization function among the nodes is not critical.

3) Data Aggregation: Distributed data aggregation and, in particular, the evaluation of the aggregated power demand, is a very important function for the correct operation of Overgrid. In recent years, various algorithms for computing a distributed sum of local parameters have been developed, with different tradeoffs in terms of accuracy, robustness, and communication overhead (see [25] for a complete survey of many commonly used tools). Most of these mechanisms evaluate the sum of the parameters available at each node by estimating an average value of these parameters and the number of nodes. The average is based on the concept of mass conservation in the network: starting from the local parameter available at each node, couples of nodes iteratively update their estimate to the same value, by averaging the local value with the neighbor one, thus conserving the sum of the estimates before and after the update. This principle is further refined in the *flow updating* averaging scheme, where the concept of *flow*, i.e., mass movement from one node to another during the estimate update, is introduced to increase robustness to message losses, which could break the principle of mass conservation [6].

In Overgrid, we use the flow updating averaging scheme because of its robustness in faulty and dynamic environments, and its prompt reaction to churn and input value changes. The scheme is used for estimating the average power demand $\hat{E}[\mathrm{load}]$ of the smart building community in a generic kth time interval, by initializing each node with its local power demand $\mathrm{load}_i(kT)$. The same scheme is used for estimating the number of nodes $\hat{n}$. In this case, one single node (e.g., the one that starts the Overgrid) is initialized with a local parameter equal to 1 and all the other nodes with a local parameter equal to 0: the number of nodes is given by the reciprocal of the resulting average value. The use of the flow updating algorithm guarantees a rapid convergence of the estimation process throughout the P2P network.

4) Load Control: Load Control is performed independently by each node, by opportunistically changing the local power demand as a function of the DSO/utility request and estimate of the total Overgrid power demand. As detailed in the next section, we assume that the power demand of each building includes a flexible part, which can be tuned without granularity constraints (being the building consumption due to the aggregation of a large number of relatively small electric appliances), and that the load control works on this flexible part.

The local scheme has to be carefully defined in order to avoid that all nodes react at the same time to the request (causing possible instabilities) and fairness problems among different peers (e.g., some nodes that consistently reduce their demand more than others). For the first issue, we implemented a delay mechanism that postpones the power reduction of the nodes for a certain random time to desynchronize the nodes among them. In particular, if d is the number of neighbors (available because of the topology management function), the power demand adaptation is triggered after a timeout randomly extracted between 0 and $d \cdot T_c$, where T_c is the flow updating convergence time given for a network whose average degree corresponds to d.[2] This delay assures that the power adaptations are slower than data aggregation time.

For the second issue, we require that each node adjusts its power demand by taking a budget on the overall power enforced by the DSO/utility, which is proportional to its contribution to the total demand estimate. Within a generic kth time interval, each node i performs the power demand adjustments as follows:

$$\mathrm{load}_i^c(kT+t) = \frac{\mathrm{load}_i(kT)}{\hat{n}(kT+t) \cdot \hat{E}[\mathrm{load}](kT+t)} \cdot \mathrm{DR}(kT)$$

where load_i^c is the controlled power demand and load_i is the flexible power demand of node i, and $t = [0, T]$. In more complex scenarios, other fairness measures could also be employed, for example, taking into account different

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[2] Note that d is the local number of neighbors (different for each node) that we use instead of the global average degree D characteristic of the P2P network. The average degree $D = E[d]$ could also be estimated with the flow updating algorithm, but this is rather an overkill.

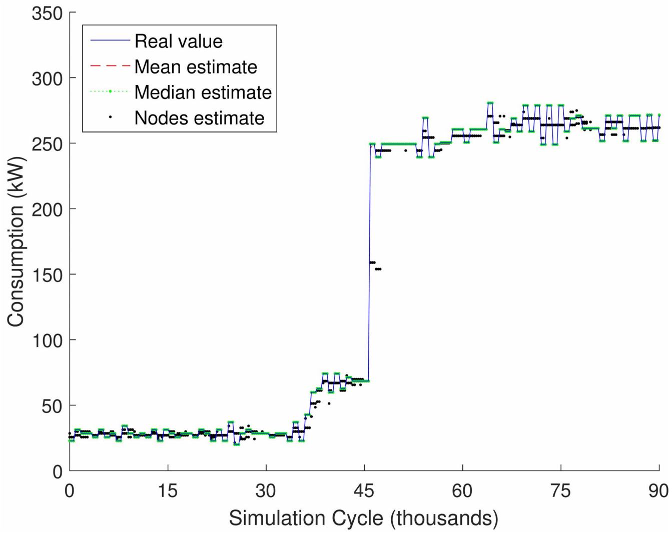

Fig. 2. Simulation trace with $n = 1000$ nodes and node degree $D = 5$.

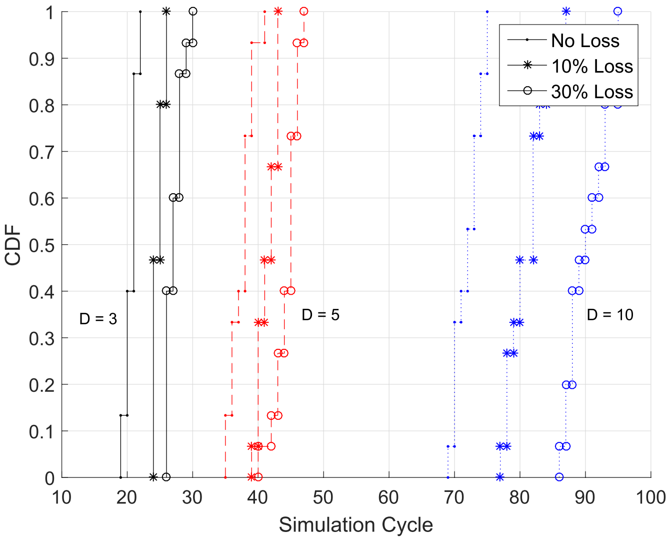

Fig. 3. CDF of the convergence time with $n = 1000$ nodes, node degree $D = 3, 5, 10$, and packet loss probability $l = 0, 0.1, 0.3$.

class of nodes (e.g., industrial versus residential) or different priorities (e.g., public safety). Note that we are merely altering the instantaneous power consumption of the nodes, omitting possible modifications of the user demands (e.g., load shifts) that we plan to include in a future work.

C. Numerical Results on Convergence Time

Although the convergence performance of flow updating has been well characterized in [6], we analyzed the applicability of this scheme in a realistic Overgrid, by comparing its convergence dynamics with typical dynamics of the flexible power demand $\text{load}_i(kT)$ generated by each node. The interactions with the load control scheme will be later evaluated in Section V.

For characterizing the flow updating effectiveness in tracking the Overgrid power demand, we used the PeerSim [26] simulator to run the distributed algorithms for information diffusion and data aggregation in a large P2P network (up to 10 000 nodes). In our simulations, we used the power traces described in the following section, which represent realistic power profiles of typical smart buildings sampled every 5 min. The network topology has been randomly generated with different node degrees and with error-prone links. At each simulation cycle, every node randomly selects a neighbor and exchanges messages. As we will show, even assuming that the message exchange rate is as low as one packet per second, in the absence of message losses, the algorithm is able to converge in less than 30 simulation cycles (i.e., 30 s). Fig. 2 shows a snapshot of a simulation trace with $n = 1000$ nodes and average node degree $D = 5$. The blue curve shows the real aggregated power demand, the points show the local estimates performed in time by different nodes, while the red dashed and green dotted lines, respectively, show the average and the median value of the local estimates. From Fig. 2, it is clear that the flow updating algorithm succeeds to track the power profile, although not all of the nodes converge to the correct value at the same time.

TABLE I
AVERAGE CONVERGENCE TIME WITH INCREASING NUMBER OF NODES, DEGREE $D = 3$, AND PACKET LOSS PROBABILITY $l = 0, 0.1, 0.3$

Nodes	100			1000			10000		
Loss prob.	0	0.1	0.3	0	0.1	0.3	0	0.1	0.3
Conv. time	26.5	23.2	32.0	20.6	24.7	27.2	25.5	26.4	29.3

We then define the *convergence time* as the time elapsed from the change of state in the Overgrid (every $T = 5$ min) to the moment where at least 90% of the nodes have correctly estimated the aggregated power demand. Fig. 3 shows the cumulative distribution function (CDF) of the convergence time with $n = 1000$ nodes, while varying the node degree $D = 3, 5, 10$ and packet loss probability $l = 0, 0.1, 0.3$. Fig. 3 shows that the algorithm is very robust to packet loss, while it suffers when the average node degree increases (confirming the findings of [6]). Nevertheless, even with $D = 10$ and packet loss as high as 30%, the average convergence time is around 1.5 min, way below the interval $T = 5$ min at which the Overgrid state evolves. Table I shows that similar results have been obtained for an increasing number of nodes $n = 100, 1000, 10\,000$, proving that flow updating scales very well with the network size and is applicable even in large P2P network scenarios.

IV. MODELING POWER DEMAND

In order to assess the performance of an Overgrid system before proceeding to real deployments, we define a methodology for providing realistic temporal traces $\text{load}_i(kT)$ of the *flexible power* demand of heterogeneous nodes (i.e., building types) in the Overgrid. A simple idea is exploiting the regular patterns of the aggregated power demand of large buildings and offices for providing power demand traces based on real data from the past. However, these traces are based on the *total power* demand observed in a given building, from which the flexible quota usable for load control has to be extracted. An alternative approach is using a building model, specified by the climate, the envelope, the lighting systems, the electric appliances, the heating and cooling systems, and the number and habits of the occupants, from which power demand traces are randomly generated by simulating the permanence times and activities of occupants. Since the simulations are based on the evolution of the overall building state over time (in terms of active appliances, cooling or heating systems, number of occupants, and thermal exchanges with the environment), it is possible to natively provide a power demand trace decomposed into flexible and nonflexible components. Specifically, power demand is considered flexible when generated by heating and cooling units, washing machines, dishwashers, and water heaters, while it is considered nonflexible when generated by lights, air circulation pumps for AC, televisions and decoders, computers, and fridges. There is also a multiplicity of other electrical loads that are active for short intervals of time and cannot be included into the list of flexible loads [27].

In our study, we used both simulations and real traces. On the one hand, we exploited building models and simulation-based results for directly generating the flexible power demand of four different buildings in our "Parco D'Orleans" campus in Palermo (namely, the student residence and the three former Faculties of Humanities, Agriculture, and Biology). On the other hand, we used historical real traces of an industrial plant (namely, the Italtel plant) in the town of Carini, collected for one year, from which we extracted the flexible power demand by modeling the industrial plant and by applying a time-varying scaling coefficient obtained in simulation. More into detail, being $\text{load}_s^{\text{TOT}}(kT)$ and $\text{load}_s(kT)$ the total and flexible power demand simulated at time kT, we derived the scaling coefficient $\alpha(kT) = \text{load}_s(kT)/\text{load}_s^{\text{TOT}}(kT)$ for extracting the flexible power demand from the total power demand in the real trace $\text{load}_r^{\text{TOT}}(kT)$ as $\alpha(kT) \cdot \text{load}_r^{\text{TOT}}(kT)$. The residential buildings and the industrial plant have been modeled through the dynamic simulation suite Energy+ [28]. Simulations have been calibrated and validated using actual thermal and electrical consumption reported on bills.

A. Industrial Building Model

Fig. 4 shows a real power consumption trace collected in a given week at the Italtel plant, from which it is evident that there is a regular daily pattern during the working days of the week and a different patter on Saturday and Sunday. Weekly patterns can obviously change during the year according to the seasons. Fig. 5 shows the CDF of the annual power consumption of our reference residential buildings and Italtel industrial site. From the curves, it is evident that in most of the cases, the building consumption is much lower than the maximum one, and therefore the control of flexible loads can be effective for reducing the infrastructure costs, which depend on the expected maximum consumption. For example, for the residential buildings, in the 90% of the cases, the consumption is lower than 125 kW, although the probability distribution sums to 1 for a power consumption higher than 175 kW.

For estimating the flexible quota of the industrial power demand, the industrial plant has been modeled by considering that the plant is extended in an area of 117 700-m^2 wide, where manufacturing, service facilities (including research and development, laboratories, and data centers), and external lightings are active. The simulator allows specifying the parameters described in what follows.

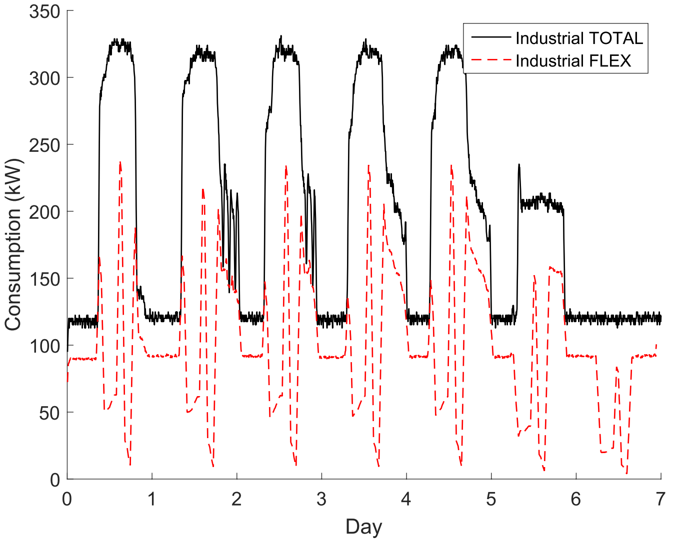

Fig. 4. Power consumption of the industrial site during a generic working week.

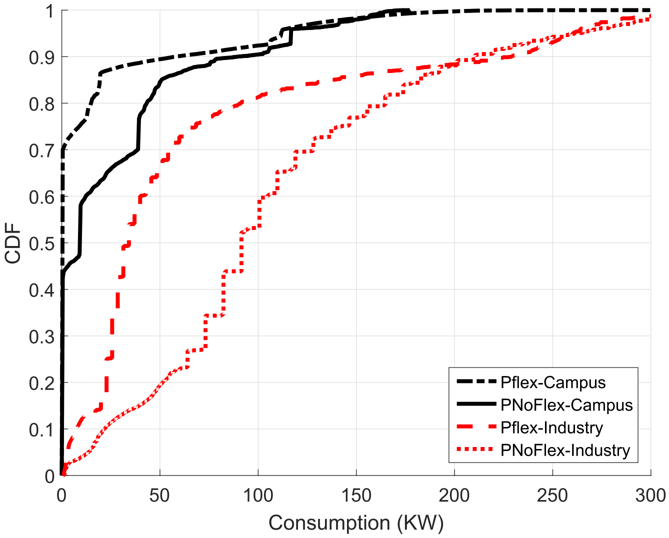

Fig. 5. CDF of the power consumption throughout 2015.

1) Research and Development Building: This building is made of three floors, with a developed surface of 4944 m^2. It hosts an open space of about 200 workstations, several rooms (offices and meeting rooms) with fixed and mobile walls. The lighting system consists of fluorescent tubes with a controlled timer operation for common spaces and autonomous switches elsewhere. The heating/cooling plant consists of two electric compressors, one for heat recovery and a heat pump, with a summer cycle of 1800 kW thermal and a winter cycle 600 kW thermal, accompanied by two air treatment units with a total flow rate of 24 000 m^3/h. The period of operation of the water heater is generally from December 1 to March 31, on Monday to Friday from 7:00 to 17:00 and adjusted according to the external climatic conditions.

2) Labs and Data Center: This building is made of prefabricated metal structures, supported by reinforced concrete pillars, with a surface of 2672 m^2. The lighting system consists of fluorescent tubes with a controlled timer operation. The building hosts a server and storage data center, a test plant, and several workstations. The air conditioning system is centralized, and the air is treated through three air treatment units with a total flow rate of 78 000 m^3/h. Power is guaranteed by two uninterruptible power systems, which also serve the research and development building.

3) External Lighting: The lighting plant consists of light poles placed at the perimeter of the buildings, street lights, and lightings for sensitive areas with halogen lamps. The light poles are equipped with lamps of 250 W. There are also two high poles with mercury vapor lamps (400 W plus four 250-W lamps).

B. Residential Building Models

Four buildings belonging to the Campus of the University of Palermo have been modeled and simulated in order to produce power demand traces of heterogeneous buildings. The simulations have been carried out for all the different seasons, which have been mapped into different habits of the occupants and environmental conditions. During the winter season, heating systems are considered 100% turned-on during the working days, according to heating season schedules of climate zone B (from December 1 to March 31). Operation of equipment and occupation responsible of internal loads have considered according to specific schedules for each typology of spaces (classrooms, offices, libraries, distribution spaces, and laboratories). For each kind of load [artificial lighting, system pumps, system fans, water heater, chiller, domestic hot water (DHW), and appliances], hourly time schedules have been considered.

The parameters specified in the simulator are summarized in the following descriptions of the buildings.

1) Graduate Housing "Santi Romano": This building is actually a cluster of three blocks having different uses: block A (dining hall and rooms), block B (distribution spaces, stairs, and reception), and block C (offices and rooms). The main structure is made of reinforced concrete. External walls and roofs do not have thermal insulation; it results in relatively high U-values (roof: 1.66 W/m^2K; wall: 1.52 W/m^2K). The windows are made of aluminum frame, without thermal break, and single glass with a U-value of 6.28 W/m^2K. Furthermore, sometimes, shading devices occur. Central heating system (water heater and radiators) is powered by natural gas and controlled by a unit controller with external temperature probe. Cooling system is present only in some spaces and into the dining hall, which also has a mechanical ventilation system. Furthermore, several room air conditioners (RACs) have been installed in the offices. Artificial lighting system consists of fluorescent lamps with manual control.

2) Agriculture Faculty: The building has four levels with different uses: laboratory, offices, classrooms, auditorium, library, common spaces, and technical rooms. Building structure is in reinforced concrete. External walls (U-value = 1.42 W/m^2K) and roof (U-value = 1.59 W/m^2K) are, respectively, made of tuff and brick concrete, without thermal insulation, while windows have frame in aluminum without thermal break and single glass (U-value = 6.28 W/m^2K). Central heating plant is composed of three natural gas boilers and radiators. The boilers have 348.9, 581.5, and 430.31 kW installed power with an average efficiency of about 0.71%. During the summer season, about 100 RACs ensure cooling requirements. Artificial lighting system consists of fluorescent tubes with powers of 18, 36, or 56 W and compact fluorescent bulbs of 60 W. The whole system has manual control.

3) Literature and Philosophy Faculty: The building is composed of a ground level where an auditorium, a computer laboratory, and several classrooms are present. Furthermore, there are also offices and classrooms from the second to the seventh floor. Structure is made of reinforced concrete, with tuff walls, without thermal insulation, and brick concrete roof. Windows have aluminum frame and single glass, without thermal break. The water central heating plant is composed of a water heater of 639 kW, powered by natural gas, and radiators. During the summer, cooling is guaranteed by 80 RACs, which also work in the winter season as heat pumps. Furthermore, in auditorium and computer laboratory, a mechanical ventilation system occurs, powered by an air handling unit. Artificial lighting system is composed of fluorescent lamps with manual turn ON/OFF control system.

4) Biology Faculty: All the spaces are conditioned by a central HVAC system that manages air changes and humidity control, while water fan coils (equipped with room thermostats) supply sensible loads into the spaces. Two air-to-water heat pumps provide hot and cold water to the system. They have winter COP = 2.3 and summer COP = 2.5. DHW is provided by electrical boilers and related consumption concerns mainly to laboratory uses. Artificial lighting sources are incandescent and fluorescent lamps without automated control. Artificial lighting system is responsible for about of 30% of the primary energy end-uses, appliances for 18%, system fans for 5%, system pumps for 7%, DHW production for 12%, and HVAC system for about of 28%.

Fig. 6 shows a trace example of the total power demand and flexible power demand simulated for the "Faculty of Agriculture" building, during a generic working week in the fall season. The trace has been obtained with the usual sampling interval of 5 min. By considering the time series generated for the whole year, we also aggregated some results for characterizing the power demand of different electric systems, called end-use, such as lighting, computers and small equipment, heating/cooling systems, and DHW. Table II shows the peak power demand of each end-use in the four different buildings of the campus.

Finally, Fig. 7 highlights the percentage composition of the electricity consumption for each building over the entire year. In all cases, most of the energy is used for the lighting system. More in detail, in the graduate housing "Santi Romano," lighting accounts for the 66%, the highest observed share. This fact occurs due to the particular use of this building. For the Agriculture Faculty, computer and equipment consumption is higher than for other buildings. With regard to cooling

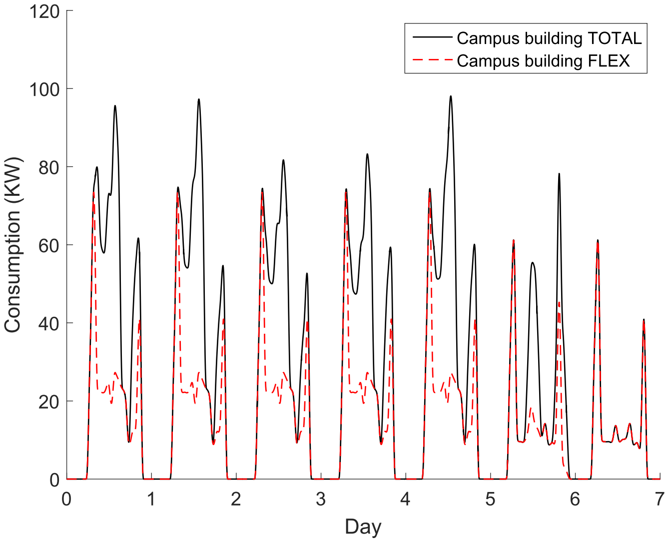

Fig. 6. Power consumption of the “Faculty of Agriculture” building during a generic working week.

TABLE II

ELECTRIC PEAK POWER PER EACH END-USE

	LIGHTING		**COMP+EQUIP**		**HEATING**		**COOLING**		**DHW**	
	kW	**W/m³**	**kW**	**W/m³**	**kW**	**W/m³**	**kW**	**W/m³**	**kW**	**W/m³**
Graduate housing	266.8	30.84	182.7	21.81	14.6	1.69	332.0	38.38	0.41	0.05
Agriculture	47.3	0.98	30.9	0.93	91.0		539.6	11.17	-	-
Literature and Philosophy	190.5	7.97	6.1	0.28	-	-	421.3 278.5*	12.35 311.85*	-	-
Biology	102.4	2.34	76.1	3.51	-	-	201.9	4.61	-	-

* Auditorium

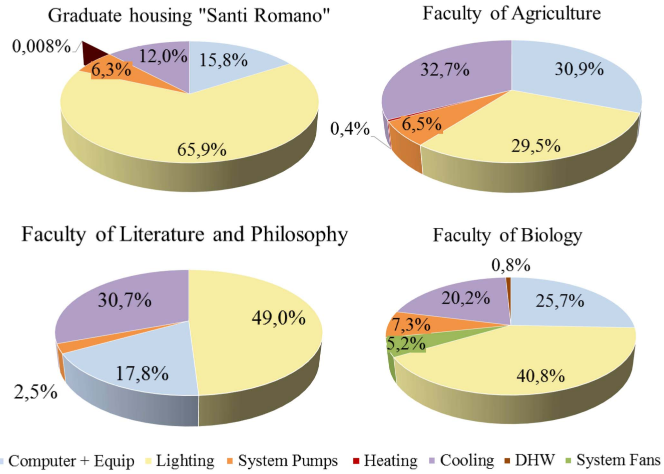

Fig. 7. Yearly electricity consumption composition for each building.

consumption, it must be noted that graduate housing has the lowest percentage values, which refers almost exclusively to the dining hall.

V. OVERGRID EXPERIMENTAL RESULTS

In order to implement the Overgrid service architecture, we developed in Java the software modules responsible of the distributed signaling mechanisms between the nodes described in Section III, by exploiting the open source library for gossip protocols called *JavaGossip* [29], which works on UDP transport packets. We also defined the load control function in another module, which is based on the local estimates of the total power demand and constrain signal sent by the DSO/utility provided by the gossip protocol. The overall service architecture is ready for a deployment on an real system, in case the software modules are connected to the power measuring system and power control actuators available in a smart building.

For testing the correct behavior of the modules and evaluating the Overgrid performance with a real communication network, we emulated the behavior of an Overgrid system, by instantiating multiple virtual machines in our laboratory at the University of Palermo running the Overgrid software modules. Each virtual machine emulates the behavior of a different smart building, by substituting the real power measurements with preloaded power demand traces and the real power control decisions with an output trace of the node internal state. An additional node with a preloaded trace with the power constraints $\mathrm{DR}(kT)$ is also created for emulating the DSO/utility behavior. Although our results are currently limited to a communication network that is basically given by a local area network, the impact of geographic communication networks can be easily tested using, for example, distributed machines available for research purposes in world-wide laboratories [30].

For emulating a significant number of smart buildings, we split the traces described in Section IV week by week (separating winter season from summer and intermediate seasons) in 72 weekly traces with the campus data and 18 weekly traces with the industrial real data. The traces were then used in parallel to compose a network of nodes with, respectively, 72 and 18 independent buildings. The evaluation was carried out by logging every 50 s both the power demand of the nodes and the average power estimate in different experiments based on random network topologies with different connectivity properties, namely, degree $D = 3, 5, 10$.

We assume that the DSO/utility requests apply for time intervals of 15 min. For generating the time series of the power constraints, we considered a wind power generation trace (sampled every 15 min) provided by a European operator [31]. This choice allows us to assess the Overgrid ability to compensate variations in wind power generation.

We first analyze the results obtained with the data from our campus buildings. From these traces, we have simulated 72 nodes with variable power consumption and repeated the experiments for various degrees of network connectivity D. As we will show from the results, the average degree D influences the speed of the P2P system, but has little impact on the ability to meet the requests of the DSO. For easiness of presentation, we report here only a subset of all the experiments produced.

Fig. 8 shows the evolution of the overall power consumption of the 72 buildings with and without DR imposed on the flexible power quota. Fig. 8 shows that Overgrid successfully

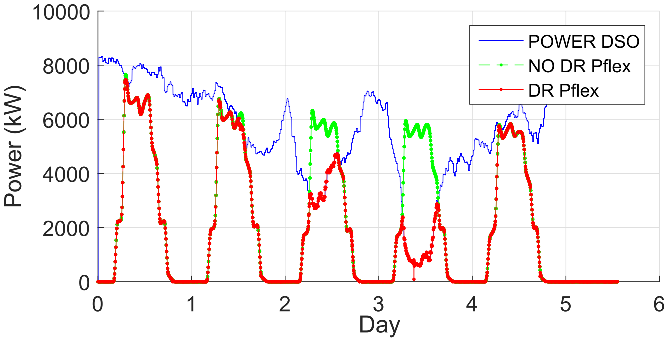

Fig. 8. Power consumption with and without DR for an Overgrid of 72 campus buildings, $D = 5$.

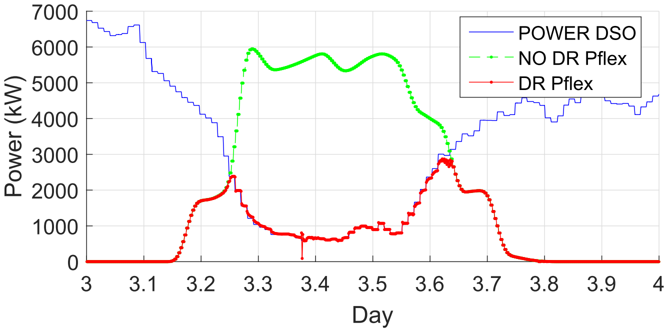

Fig. 9. Power consumption for an Overgrid of 72 campus buildings, detail of day 3.

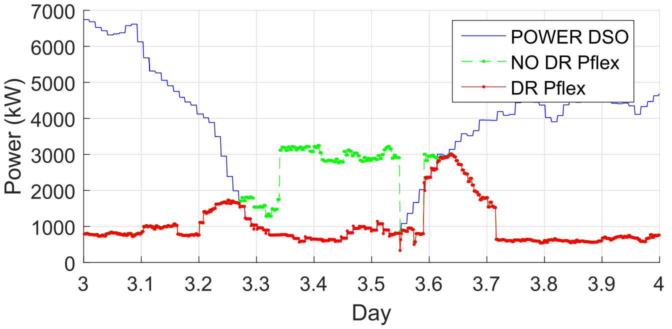

Fig. 10. Power consumption for an Overgrid of 18 industrial sites, detail of day 3.

responds to the DSO/utility requests, even in the presence of sharp changes (e.g., in day 3, from 6 down to 1 MW in less than 5 h). This is better visible in Fig. 9, which shows the detail of day 3 where the DSO variations are most demanding.

The same experiment was repeated with the power trace from the industrial site, emulating 18 different nodes with variable node degree D, and in Fig. 10, we show a sample of the result with $D = 5$ during the same day 3. Form Fig. 10, it is clear that Overgrid is able to correctly respond to the DSO requests of modulating the power consumption.

To assess the performance of Overgrid more quantitatively, we analyzed the "deviations" (relative error) of the total power load against the DSO requests, i.e., when $\sum_{i=1}^{n} \text{load}_i(t) > \text{DR}(t)$. Fig. 11 shows the CDF of these deviations for the campus building traces, while we omit the results obtained with the industrial site trace that are similar. Fig. 11 shows that by choosing as small node degree such as $D = 3$, Overgrid shows no errors at all for over 90% of the time and less than 3% error in about 97% of the cases. This also confirms our simulation results that flow updating works best with small values of D. However, independently from the node degree D, Fig. 11 also suggests that the value of D has little impact on the Overgrid ability to respond to the DSO requests, which performs very well overall, since with higher values of D, Overgrid is still able to track the DSO requests in over 95% of the cases with a maximum error of 10%.

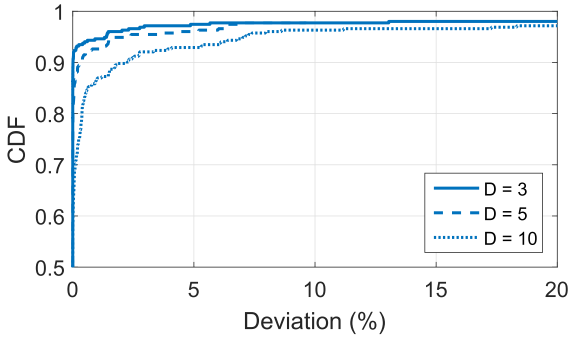

Fig. 11. CDF of the Overgrid deviations from DSO requests.

VI. CONCLUSION

In this paper, we presented Overgrid, a fully distributed P2P architecture designed to automatically control and implement distributed DR schemes in a community of smart buildings. Overgrid is able to control the power consumption of residential buildings, as belonging to a virtual microgrid, regardless of their physical location. In the implementation of Overgrid, we make use of an innovative averaging mechanism, the flow updating, for distributedly monitoring the power consumption of the buildings and the number of nodes in the network. We explored the applicability of flow updating in the Overgrid scenario, using a P2P network simulator, and assessed the performance of this algorithm with realistic power profiles in large networks, with up to 10 000 nodes. We accurately studied the energy characteristics of several types of buildings in our university campus providing some reference models and classifying the amount of flexible energy, the power available for DR programs. Finally, we experimentally validated Overgrid by emulating a real P2P network of smart buildings behaving accordingly to our reference models, demonstrating the feasibility of our approach.

We are currently working on different extensions of our approach for taking into account the possibility to: 1) aggregate buildings with complementary behaviors, capable of operating power consumption modulation all year round; 2) introduce prioritization mechanisms for power reduction; and 3) include storage for improving the integration of renewable source production.

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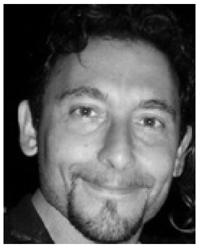

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Overgrid: A Fully Distributed Demand Response Architecture Based on Overlay Networks

Daniele Croce, Fabrizio Giuliano, Ilenia Tinnirello, Alessandra Galatioto,
Marina Bonomolo, Marco Beccali, and Gaetano Zizzo

***Abstract*— In this paper, we present *Overgrid*, a fully distributed peer-to-peer (P2P) architecture designed to automatically control and implement distributed demand response (DR) schemes in a community of smart buildings with energy generation and storage capabilities. As overlay networks in communications establish logical links between peers regardless of the physical topology of the network, the Overgrid is able to apply some power balance criteria to its system of buildings, as they belong to a virtual microgrid, regardless of their physical location. We exploit an innovative distributed algorithm, called flow updating, for monitoring the power consumption of the buildings and the number of nodes in the network, proving its applicability in an Overgrid scenario with realistic power profiles and networks of up to 10 000 buildings. To quantify the energy balance capability of Overgrid, we first study the energy characteristics of several types of buildings in our university campus and in an industrial site to accurately provide some reference buildings models. Then, we classify the amount of "flexible" energy consumption, i.e., the quota that could be potentially exploited for DR programs. Finally, we validate Overgrid emulating a real P2P network of smart buildings behaving according to our reference models. The experimental results prove the feasibility of our approach.**

***Note to Practitioners*—In this paper, we propose a scalable solution for supporting distributed load control in a community of smart buildings, whose deployment requires minimal communication overhead and no dedicated investments for the control network. The control system, called Overgrid, is implemented over an unstructured peer-to-peer (P2P) overlay based on gossiping, a commonly used paradigm allowing a strong and scalable information diffusion (fault tolerant) across the network, totally decentralized, and with low network overhead. Overgrid creates the P2P network over the electrical grid (thus the name Overgrid), in which the management of electrical loads is carried out by the nodes participating in the network through innovative distributed algorithms. We exploit a one-year study of power consumption traces in a reference industrial site and simulation-based traces for residential buildings, in order to test the effectiveness of our solution in realistic scenarios.**

***Index Terms*— Gossiping, overlay networks, peer-to-peer (P2P), smart grid.**

I. INTRODUCTION

TRADITIONALLY, energy demand was much more variable and less controllable than supply, so energy balance was achieved by adapting dynamically generation levels to match consumption. Now, the increasing penetration of unpredictable renewable energy has radically changed the situation. Wind and solar generation experiences intermittency, a combination of noncontrollable variability and partial unpredictability, and depends on resources that are location dependent [1]. It follows that the integration of these energy sources into electric grids requires an increment of the power system flexibility, which can be achieved both by considering efficient integration of energy resources (widely studied since 1997 [2]) and the control of location-dependent power demand. Two common approaches for controlling the power demand are commonly classified as *reactive* and *dispatchable* demand response (DR). The former refers to the possibility of end users changing their normal consumption patterns in response to a dynamic price signal; the latter (also called load control) refers to the possibility of the energy utility or third party entities of directly switching some specific user appliances off during peak demand periods or tuning their operation conditions for reducing the power demand.

In this paper, we deal with load control mechanisms working on the aggregation of a number of smart buildings, i.e., buildings equipped with Internet connectivity and a local communication network for the control of electric smart appliances. Indeed, most of the current load control programs work on large industrial loads or domestic thermostatic loads. Large industrial loads have a significant and well characterized power demand and can be disconnected according to prearranged agreements between the energy utility and the customer with very simple decisions and control networks [3]. Domestic thermostatic loads, such as air conditioners and heating systems, allow a fine-tuning regulation of power demand [4], but require to involve a very large number of customers, thus making the control algorithms more complex [5]. The aggregation of smart buildings represents an intermediate solution between the extreme case of large industrial customers or independent residential customers, and a good tradeoff between the power demand flexibility (e.g., maximum amount of power shift that can be achieved) and complexity of the control system.

The reference smart buildings considered in our study are four buildings of our campus, whose consumption patterns have been characterized and modeled as detailed in Section IV, and an industrial research center that works in proximity of the campus. We propose a completely distributed solution

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for supporting the creation, maintenance, and operation of a community of buildings, whose power demand is similar to our reference buildings, which jointly participate to the load control program. The solution is based on two main aspects: 1) using Internet and a peer-to-peer (P2P) communication model for creating the control network between the buildings, without any dedicated investment for servers and communication infrastructures[1] and 2) using gossip-based protocols for estimating the aggregate power demand of the community and responding to the load modulation requests, as detailed in Section III. We call the community of buildings participating to the load control program an *Overgrid*. Indeed, in case smart buildings are also equipped with local generation and storage systems, the system as a whole can act as a virtual microgrid, which is not able to work independently from the electric grid, but can be independent in terms of overall energy balance.

In the implementation of Overgrid, we make use of an innovative algorithm, namely, flow updating [6], for distributedly monitoring the state of the P2P network. To prove the feasibility of our approach, we emulated the behavior of an Overgrid by setting up a virtual network of buildings whose power demand was simulated according to our reference building models. We analyzed the performance of the Overgrid gossip protocol for aggregating the building power demand and responding to different power reduction signals, as the connectivity degree of the network varies, demonstrating the applicability of flow updating with realistic power profiles and distributed networks of up to 10 000 buildings. Our results show that the system is quite robust to topological changes and message losses, the adaption times are compatible with the typical times expected for DR mechanisms, and generalization to systems at different (larger or smaller) scales is possible. Therefore, we argue that our solution can be of practical interest in many emerging scenarios, in which consumers can be aggregated without the need of third party operators.

II. RELATED WORK

A. Communication Infrastructures for Load Control

Load control can work at different levels in the energy grid, for attenuating voltage regulation problems (primary level), enforcing desired consumption profiles (secondary/tertiary level), affecting the electricity market (price zone level), thus achieving the heterogeneous goals of improving the grid reliability [7], or performing operation savings [8]. Different players can be involved into the program: the energy supplier can interact with the distribution system operators (DSOs) and/or with novel intermediate figures called load aggregators [9], before reaching the final consumers and enforcing a change in their power demand. While the involvement of the DSO has some obvious implications for the maintenance of the electric grid, the presence of the load aggregator is envisioned for introducing an intermediary, which simplifies the interaction with large numbers of consumers. Moreover, the aggregator can collect information on user profiles and willingness to respond to control actions for dispatching the controlled loads as a response of the higher level commands. In all the cases, the control program requires an underlying communication infrastructure that allows the necessary information exchange between the different players (energy utility, DSO, industrial or residential users, load aggregators, etc.) and domains [low-voltage (LV), medium-voltage, or high-voltage (HV) grid segments, price zone, etc.] involved in the program.

Direct load control programs have been activated in pilot projects for both residential and industrial customers. For residential customers, some utilities also offer commercial services [10] based on the deployment of radio-controlled switches on air-conditioning units or electric water heaters at the customers' premises. For industrial customers, the control mechanisms are very simple and often based on voice dispatch (i.e., a telephone network) [3]. Conversely, for large-scale deployments working on residential users [11], alternative communication infrastructures have to be considered. In case the DSO is involved into the control program, it is possible to utilize the advanced metering infrastructure, mainly based on PLC (where possible) and GPRS technologies, for transporting load control signals [12]. Conversely, Internet connections available in most households may enable more flexible programs managed by third parties [13]. In this case, the supplier can communicate to the load aggregator requesting not to exceed a maximum absorbed power during a specific time interval [14] or to exceed a given power demand with a probability smaller than a desired bound [15].

B. Service Architecture

Most of the current load control programs are centralized: control decisions are taken by the DSO, energy supplier, or load aggregator on the basis of dynamic programming optimization [5], fuzzy logic-based decisions [16], or other profit maximization schemes [17], and enforced to the customers. Even in the case of decentralized dispatch based on price signals that affect the user decisions [18] (without providing any guarantee), price signals are decided at a central level. In other words, load control is mostly based on a traditional client–server service architecture, in which a global server maintains the links with each industrial or residential customer for dispatching control/price messages and collecting monitoring data.

For large-scale load control working on residential users, scalability and reliability could be critical issues because it is required to interact with large number of users and communication links. A different service architecture based on P2P communications could respond to these requirements better than client-service architectures, by explicitly dealing with the potential increment of the communication delays [19]. In P2P networks, all the nodes have equivalent functionalities and keep contacts with a subset of nodes, called neighbors, rather than communicating with a single server. These features make P2P networks very effective to create large-scale distributed applications over the Internet, such as on-demand distribution of video content and video streaming [20]. The possibility to exploit P2P networks in smart grid applications has been

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[1] We assume the Internet connection to be already available for the participating peers and that a gateway or local "energy manager" runs the proposed algorithms in each building.

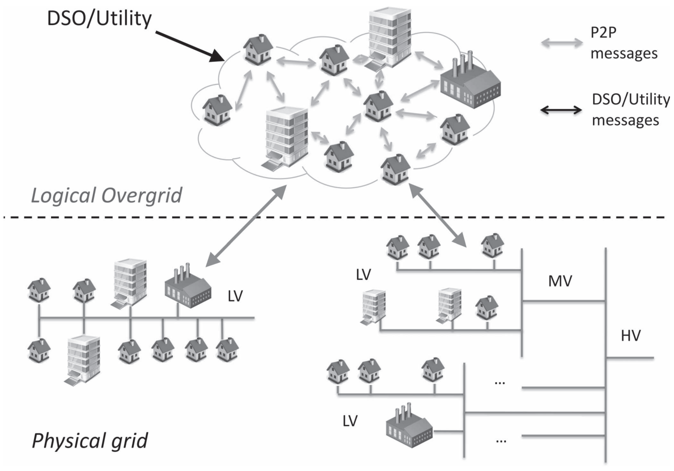

Fig. 1. Reference scenario for the Overgrid.

discussed mainly for secondary and tertiary control on a microgrid [21], or for disseminating and aggregating information in the metering infrastructure [22], [23]. In our work, we propose a similar approach to the load control problem, by enabling the creation of a completely distributed community of smart buildings, which participate to the program without intermediaries.

III. OVERGRID CONCEPT

The key idea in Overgrid is the generalization of the concept of microgrid, from a *localized system* of loads and energy resources, which can be disconnected from the main grid, to a *virtual community* of smart buildings equipped with controllable loads, local generators, and storage systems, which cannot work in isolation, but can support a desired energy balance with the main grid.

Fig. 1 represents the Overgrid concept; by enlightening, that group of buildings (also called nodes) participating to the Overgrid can be mapped to different placements on the energy grid: on the same LV segment, as shown in the left case, in different LV segments in the same HV segment, as shown in the right case, or even in independent distribution networks in the same price zone. Indeed, multiple criteria can be considered for clustering the smart buildings in an Overgrid, such as physical proximity in an edge part of the distribution network, complementary power demands that allow exhibiting a stable aggregated demand, similar equipment for energy storage or load control that allows supporting homogeneous control actions, and types of contracts with the energy utility. Regardless of the specific clustering criterion, which is out of the scope of this paper, the goal of the community is trying to guarantee a desired power balance with the rest of the grid, according to a dynamic signal $\mathrm{DR}(t)$ provided by the DSO or energy utility. For a community of n nodes, being $\mathrm{load}_i(t)$ the power demand of node i at time t (which can be negative for taking into account local generation systems), the instantaneous balance can be expressed as $\sum_{i=1}^{n} \mathrm{load}_i(t) = \mathrm{DR}(t)$.

The dynamic constraint $\mathrm{DR}(t)$ can be equal to zero for imposing that the Overgrid is energetically independent from the rest of the grid, or lower than zero for imposing that the Overgrid provides power to the rest of the grid. Note that the power demand of each building is measured by sampling the real consumption at regular time intervals T (typically of 5 min), and similarly the signal constraint is a piecewise constant function that imposes the same constraint during a time interval of kT (typically 15 min, i.e., $3 \cdot T$). It follows that the previous balance condition can be considered as a discrete-time condition, if we consider both the power demand measurements and the power constraints as time series with a common sampling interval T.

To achieve the desired power balance, we consider a completely distributed service architecture, based on P2P communications. A distributed control protocol allows each node to estimate the aggregated power demand and constraint of the Overgrid in a given time interval, without inquiring any centralized server, and to implement a local load control in order to meet the desired balance.

A. Architecture Overview

We assume that each smart building joining the Overgrid is equipped with an Internet connection for exchanging control messages with the other nodes of the community. Moreover, a local communication network (based on WiFi, ZigBee, power line, etc.) is available for controlling the electric appliances and/or the production and storage systems, with a response time comparable with the Internet latency (in general, up to few seconds). The specification of the technology for supporting the *local* communication network and load control is out of the scope of this paper.

On top of the physical communication network between the nodes, Overgrid implements an unstructured P2P overlay network, where nodes do not have *a priori* knowledge of the topology and communicate with the neighbors by means of gossip protocols [24]. Gossip protocol scalability comes from the fact that each node is in communication with a subset of other nodes (typically much smaller than the entire size of the network), which represents the neighbors of the node. This architecture is intrinsically fault tolerant, totally decentralized, and with low network overhead. No dedicated server or other centralized resources are required for creating the "community" of smart buildings.

The Overgrid gossip protocol works according to a generic push–pull structure. Each node executes a main loop for sending, at regular time intervals, a message containing its local state to a random neighbor (*active thread*). Upon the reception of a message, the neighbor replies with another message, sending back its local state to the node starting the message exchange (*passive thread*). Both the nodes involved in the message exchange update their local state as a function of the information fields transmitted by the peer node. Finally, each node runs independently several distributed functions to maintain the connectivity of the P2P network, for disseminating information to the neighbors, for data aggregation and estimation of network-wide parameters and distributed load control.

B. Distributed Functions

The gossip protocol is responsible of three different aspects: 1) building and maintaining the network topology; 2) disseminating information about $\mathrm{DR}(kT)$ among the Overgrid nodes; and 3) aggregating local data for estimating the overall power demand $\sum_i \mathrm{load}_i(kT)$. Three independent local state components are used for managing the information relevant to these aspects. Gossip messages can include one or more of these state components, while peer sampling is always based on random selection. On the basis of the local estimate of the total power demand and power constraint, each node has finally to perform a load control scheme.

1) Topology Management: The local state used for building and maintaining of the P2P network is given by the list of neighbor nodes and by the relevant activity indicators (also called *heartbeat*). Messages transporting this local state are generated at fixed time intervals and are usually independent from the messages used for disseminating or aggregating data in the network. The heartbeat of a given neighbor is increased of one unit when a message (of any type) is received by that neighbor, while the neighbor list is updated when a node receives a message from a new neighbor or when a neighbor is inactive for a long time interval. When a node is activated for the first time, a local configuration file provides an initial neighbor list that contains at least one neighbor node. The list is updated after the node exchanges the first message with a neighbor, by learning about the neighbors of the neighbor.

2) Information Dissemination: Information dissemination is used for notifying the power demand constraint, which is received at regular time intervals by a random node of the P2P network, to all the nodes. The local state is given by last received power constraint and by the timestamp indicating when the data have been generated. Nodes update the local state to a new value when they receive a message with a more recent timestamp. This requires that a common reference time is available at each node. Because the load control dynamics considered in our work evolve at scales of the order of several minutes (typically, 15 min), such a synchronization function among the nodes is not critical.

3) Data Aggregation: Distributed data aggregation and, in particular, the evaluation of the aggregated power demand, is a very important function for the correct operation of Overgrid. In recent years, various algorithms for computing a distributed sum of local parameters have been developed, with different tradeoffs in terms of accuracy, robustness, and communication overhead (see [25] for a complete survey of many commonly used tools). Most of these mechanisms evaluate the sum of the parameters available at each node by estimating an average value of these parameters and the number of nodes. The average is based on the concept of mass conservation in the network: starting from the local parameter available at each node, couples of nodes iteratively update their estimate to the same value, by averaging the local value with the neighbor one, thus conserving the sum of the estimates before and after the update. This principle is further refined in the *flow updating* averaging scheme, where the concept of *flow*, i.e., mass movement from one node to another during the estimate update, is introduced to increase robustness to message losses, which could break the principle of mass conservation [6].

In Overgrid, we use the flow updating averaging scheme because of its robustness in faulty and dynamic environments, and its prompt reaction to churn and input value changes. The scheme is used for estimating the average power demand $\hat{E}[\mathrm{load}]$ of the smart building community in a generic kth time interval, by initializing each node with its local power demand $\mathrm{load}_i(kT)$. The same scheme is used for estimating the number of nodes $\hat{n}$. In this case, one single node (e.g., the one that starts the Overgrid) is initialized with a local parameter equal to 1 and all the other nodes with a local parameter equal to 0: the number of nodes is given by the reciprocal of the resulting average value. The use of the flow updating algorithm guarantees a rapid convergence of the estimation process throughout the P2P network.

4) Load Control: Load Control is performed independently by each node, by opportunistically changing the local power demand as a function of the DSO/utility request and estimate of the total Overgrid power demand. As detailed in the next section, we assume that the power demand of each building includes a flexible part, which can be tuned without granularity constraints (being the building consumption due to the aggregation of a large number of relatively small electric appliances), and that the load control works on this flexible part.

The local scheme has to be carefully defined in order to avoid that all nodes react at the same time to the request (causing possible instabilities) and fairness problems among different peers (e.g., some nodes that consistently reduce their demand more than others). For the first issue, we implemented a delay mechanism that postpones the power reduction of the nodes for a certain random time to desynchronize the nodes among them. In particular, if d is the number of neighbors (available because of the topology management function), the power demand adaptation is triggered after a timeout randomly extracted between 0 and $d \cdot T_c$, where T_c is the flow updating convergence time given for a network whose average degree corresponds to d.[2] This delay assures that the power adaptations are slower than data aggregation time.

For the second issue, we require that each node adjusts its power demand by taking a budget on the overall power enforced by the DSO/utility, which is proportional to its contribution to the total demand estimate. Within a generic kth time interval, each node i performs the power demand adjustments as follows:

$$\mathrm{load}_i^c(kT+t) = \frac{\mathrm{load}_i(kT)}{\hat{n}(kT+t) \cdot \hat{E}[\mathrm{load}](kT+t)} \cdot \mathrm{DR}(kT)$$

where load_i^c is the controlled power demand and load_i is the flexible power demand of node i, and $t = [0, T]$. In more complex scenarios, other fairness measures could also be employed, for example, taking into account different

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[2] Note that d is the local number of neighbors (different for each node) that we use instead of the global average degree D characteristic of the P2P network. The average degree $D = E[d]$ could also be estimated with the flow updating algorithm, but this is rather an overkill.

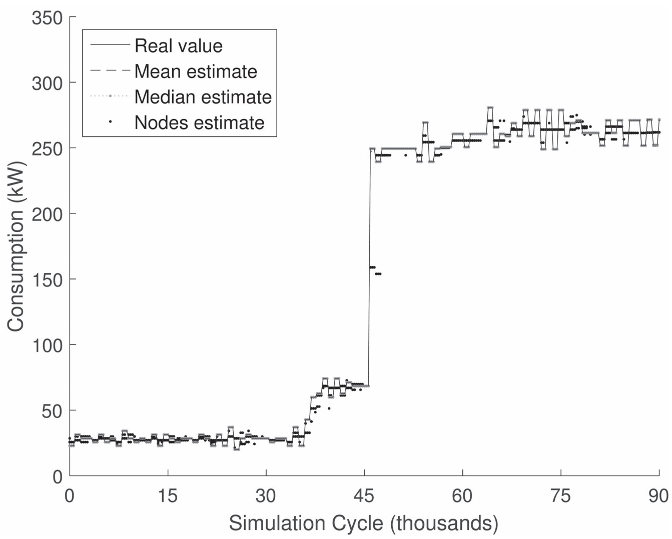

Fig. 2. Simulation trace with $n = 1000$ nodes and node degree $D = 5$.

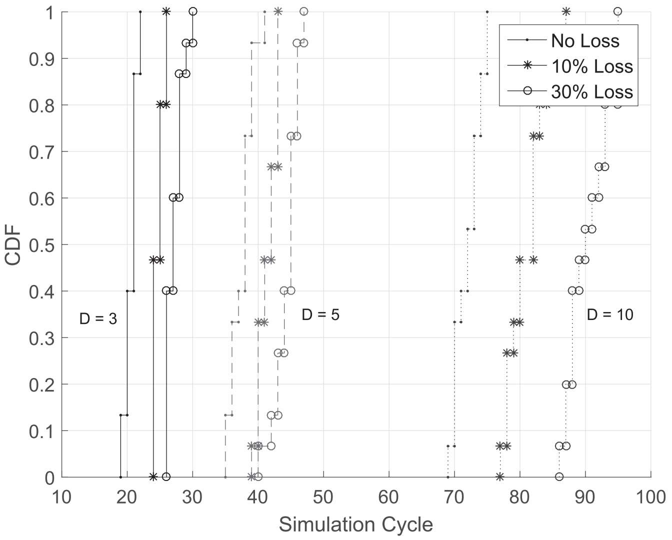

Fig. 3. CDF of the convergence time with $n = 1000$ nodes, node degree $D = 3, 5, 10$, and packet loss probability $l = 0, 0.1, 0.3$.

class of nodes (e.g., industrial versus residential) or different priorities (e.g., public safety). Note that we are merely altering the instantaneous power consumption of the nodes, omitting possible modifications of the user demands (e.g., load shifts) that we plan to include in a future work.

C. Numerical Results on Convergence Time

Although the convergence performance of flow updating has been well characterized in [6], we analyzed the applicability of this scheme in a realistic Overgrid, by comparing its convergence dynamics with typical dynamics of the flexible power demand $\text{load}_i(kT)$ generated by each node. The interactions with the load control scheme will be later evaluated in Section V.

For characterizing the flow updating effectiveness in tracking the Overgrid power demand, we used the PeerSim [26] simulator to run the distributed algorithms for information diffusion and data aggregation in a large P2P network (up to 10 000 nodes). In our simulations, we used the power traces described in the following section, which represent realistic power profiles of typical smart buildings sampled every 5 min. The network topology has been randomly generated with different node degrees and with error-prone links. At each simulation cycle, every node randomly selects a neighbor and exchanges messages. As we will show, even assuming that the message exchange rate is as low as one packet per second, in the absence of message losses, the algorithm is able to converge in less than 30 simulation cycles (i.e., 30 s). Fig. 2 shows a snapshot of a simulation trace with $n = 1000$ nodes and average node degree $D = 5$. The blue curve shows the real aggregated power demand, the points show the local estimates performed in time by different nodes, while the red dashed and green dotted lines, respectively, show the average and the median value of the local estimates. From Fig. 2, it is clear that the flow updating algorithm succeeds to track the power profile, although not all of the nodes converge to the correct value at the same time. We then define the *convergence time* as the time elapsed from the change of state in the Overgrid (every $T = 5$ min) to the moment where at least 90% of the nodes have correctly estimated the aggregated power demand. Fig. 3 shows the cumulative distribution function (CDF) of the convergence time with $n = 1000$ nodes, while varying the node degree $D = 3, 5, 10$ and packet loss probability $l = 0, 0.1, 0.3$. Fig. 3 shows that the algorithm is very robust to packet loss, while it suffers when the average node degree increases (confirming the findings of [6]). Nevertheless, even with $D = 10$ and packet loss as high as 30%, the average convergence time is around 1.5 min, way below the interval $T = 5$ min at which the Overgrid state evolves. Table I shows that similar results have been obtained for an increasing number of nodes $n = 100, 1000, 10\,000$, proving that flow updating scales very well with the network size and is applicable even in large P2P network scenarios.

TABLE I
AVERAGE CONVERGENCE TIME WITH INCREASING NUMBER OF NODES, DEGREE $D = 3$, AND PACKET LOSS PROBABILITY $l = 0, 0.1, 0.3$

Nodes	100			1000			10000		
Loss prob.	0	0.1	0.3	0	0.1	0.3	0	0.1	0.3
Conv. time	26.5	23.2	32.0	20.6	24.7	27.2	25.5	26.4	29.3

IV. MODELING POWER DEMAND

In order to assess the performance of an Overgrid system before proceeding to real deployments, we define a methodology for providing realistic temporal traces $\text{load}_i(kT)$ of the *flexible power* demand of heterogeneous nodes (i.e., building types) in the Overgrid. A simple idea is exploiting the regular patterns of the aggregated power demand of large buildings and offices for providing power demand traces based on real data from the past. However, these traces are based on the *total power* demand observed in a given building, from which the flexible quota usable for load control has to be extracted. An alternative approach is using a building model, specified by the climate, the envelope, the lighting systems, the electric appliances, the heating and cooling systems, and the number and habits of the occupants, from which power demand traces are randomly generated by simulating the permanence times and activities of occupants. Since the simulations are based on the evolution of the overall building state over time (in terms of active appliances, cooling or heating systems, number of occupants, and thermal exchanges with the environment), it is possible to natively provide a power demand trace decomposed into flexible and nonflexible components. Specifically, power demand is considered flexible when generated by heating and cooling units, washing machines, dishwashers, and water heaters, while it is considered nonflexible when generated by lights, air circulation pumps for AC, televisions and decoders, computers, and fridges. There is also a multiplicity of other electrical loads that are active for short intervals of time and cannot be included into the list of flexible loads [27].

In our study, we used both simulations and real traces. On the one hand, we exploited building models and simulation-based results for directly generating the flexible power demand of four different buildings in our "Parco D'Orleans" campus in Palermo (namely, the student residence and the three former Faculties of Humanities, Agriculture, and Biology). On the other hand, we used historical real traces of an industrial plant (namely, the Italtel plant) in the town of Carini, collected for one year, from which we extracted the flexible power demand by modeling the industrial plant and by applying a time-varying scaling coefficient obtained in simulation. More into detail, being $\mathrm{load}_s^{\mathrm{TOT}}(kT)$ and $\mathrm{load}_s(kT)$ the total and flexible power demand simulated at time kT, we derived the scaling coefficient $\alpha(kT) = \mathrm{load}_s(kT)/\mathrm{load}_s^{\mathrm{TOT}}(kT)$ for extracting the flexible power demand from the total power demand in the real trace $\mathrm{load}_r^{\mathrm{TOT}}(kT)$ as $\alpha(kT)\cdot\mathrm{load}_r^{\mathrm{TOT}}(kT)$. The residential buildings and the industrial plant have been modeled through the dynamic simulation suite Energy+ [28]. Simulations have been calibrated and validated using actual thermal and electrical consumption reported on bills.

A. Industrial Building Model

Fig. 4 shows a real power consumption trace collected in a given week at the Italtel plant, from which it is evident that there is a regular daily pattern during the working days of the week and a different patter on Saturday and Sunday. Weekly patterns can obviously change during the year according to the seasons. Fig. 5 shows the CDF of the annual power consumption of our reference residential buildings and Italtel industrial site. From the curves, it is evident that in most of the cases, the building consumption is much lower than the maximum one, and therefore the control of flexible loads can be effective for reducing the infrastructure costs, which depend on the expected maximum consumption. For example, for the residential buildings, in the 90% of the cases, the consumption is lower than 125 kW, although the probability distribution sums to 1 for a power consumption higher than 175 kW.

For estimating the flexible quota of the industrial power demand, the industrial plant has been modeled by considering that the plant is extended in an area of 117 700-m^2 wide, where manufacturing, service facilities (including research and development, laboratories, and data centers), and external lightings are active. The simulator allows specifying the parameters described in what follows.

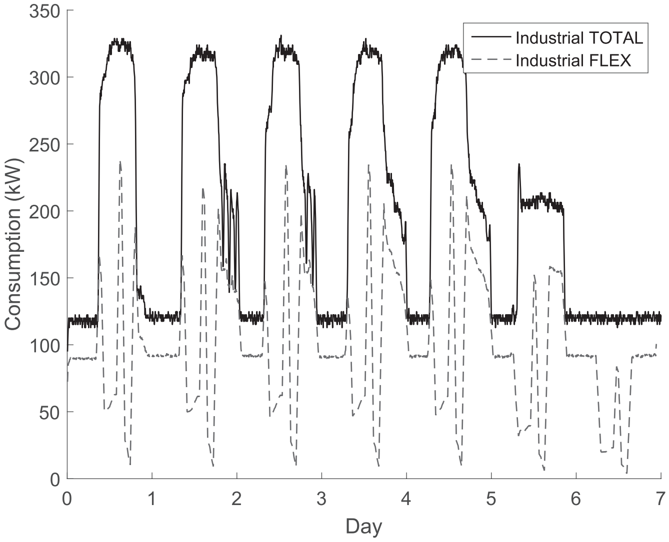

Fig. 4. Power consumption of the industrial site during a generic working week.

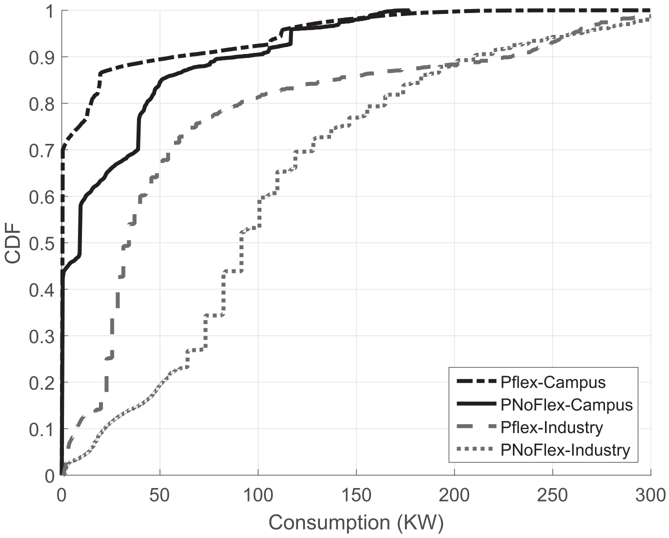

Fig. 5. CDF of the power consumption throughout 2015.

1) Research and Development Building: This building is made of three floors, with a developed surface of 4944 m^2. It hosts an open space of about 200 workstations, several rooms (offices and meeting rooms) with fixed and mobile walls. The lighting system consists of fluorescent tubes with a controlled timer operation for common spaces and autonomous switches elsewhere. The heating/cooling plant consists of two electric compressors, one for heat recovery and a heat pump, with a summer cycle of 1800 kW thermal and a winter cycle 600 kW thermal, accompanied by two air treatment units with a total flow rate of 24 000 m^3/h. The period of operation of the water heater is generally from December 1 to March 31, on Monday to Friday from 7:00 to 17:00 and adjusted according to the external climatic conditions.

2) Labs and Data Center: This building is made of prefabricated metal structures, supported by reinforced concrete pillars, with a surface of 2672 m^2. The lighting system consists of fluorescent tubes with a controlled timer operation. The building hosts a server and storage data center, a test plant, and several workstations. The air conditioning system is centralized, and the air is treated through three air treatment units with a total flow rate of 78 000 m^3/h. Power is guaranteed by two uninterruptible power systems, which also serve the research and development building.

3) External Lighting: The lighting plant consists of light poles placed at the perimeter of the buildings, street lights, and lightings for sensitive areas with halogen lamps. The light poles are equipped with lamps of 250 W. There are also two high poles with mercury vapor lamps (400 W plus four 250-W lamps).

B. Residential Building Models

Four buildings belonging to the Campus of the University of Palermo have been modeled and simulated in order to produce power demand traces of heterogeneous buildings. The simulations have been carried out for all the different seasons, which have been mapped into different habits of the occupants and environmental conditions. During the winter season, heating systems are considered 100% turned-on during the working days, according to heating season schedules of climate zone B (from December 1 to March 31). Operation of equipment and occupation responsible of internal loads have considered according to specific schedules for each typology of spaces (classrooms, offices, libraries, distribution spaces, and laboratories). For each kind of load [artificial lighting, system pumps, system fans, water heater, chiller, domestic hot water (DHW), and appliances], hourly time schedules have been considered.

The parameters specified in the simulator are summarized in the following descriptions of the buildings.

1) Graduate Housing "Santi Romano": This building is actually a cluster of three blocks having different uses: block A (dining hall and rooms), block B (distribution spaces, stairs, and reception), and block C (offices and rooms). The main structure is made of reinforced concrete. External walls and roofs do not have thermal insulation; it results in relatively high U-values (roof: 1.66 W/m^2K; wall: 1.52 W/m^2K). The windows are made of aluminum frame, without thermal break, and single glass with a U-value of 6.28 W/m^2K. Furthermore, sometimes, shading devices occur. Central heating system (water heater and radiators) is powered by natural gas and controlled by a unit controller with external temperature probe. Cooling system is present only in some spaces and into the dining hall, which also has a mechanical ventilation system. Furthermore, several room air conditioners (RACs) have been installed in the offices. Artificial lighting system consists of fluorescent lamps with manual control.

2) Agriculture Faculty: The building has four levels with different uses: laboratory, offices, classrooms, auditorium, library, common spaces, and technical rooms. Building structure is in reinforced concrete. External walls (U-value = 1.42 W/m^2K) and roof (U-value = 1.59 W/m^2K) are, respectively, made of tuff and brick concrete, without thermal insulation, while windows have frame in aluminum without thermal break and single glass (U-value = 6.28 W/m^2K). Central heating plant is composed of three natural gas boilers and radiators. The boilers have 348.9, 581.5, and 430.31 kW installed power with an average efficiency of about 0.71%. During the summer season, about 100 RACs ensure cooling requirements. Artificial lighting system consists of fluorescent tubes with powers of 18, 36, or 56 W and compact fluorescent bulbs of 60 W. The whole system has manual control.

3) Literature and Philosophy Faculty: The building is composed of a ground level where an auditorium, a computer laboratory, and several classrooms are present. Furthermore, there are also offices and classrooms from the second to the seventh floor. Structure is made of reinforced concrete, with tuff walls, without thermal insulation, and brick concrete roof. Windows have aluminum frame and single glass, without thermal break. The water central heating plant is composed of a water heater of 639 kW, powered by natural gas, and radiators. During the summer, cooling is guaranteed by 80 RACs, which also work in the winter season as heat pumps. Furthermore, in auditorium and computer laboratory, a mechanical ventilation system occurs, powered by an air handling unit. Artificial lighting system is composed of fluorescent lamps with manual turn ON/OFF control system.

4) Biology Faculty: All the spaces are conditioned by a central HVAC system that manages air changes and humidity control, while water fan coils (equipped with room thermostats) supply sensible loads into the spaces. Two air-to-water heat pumps provide hot and cold water to the system. They have winter COP = 2.3 and summer COP = 2.5. DHW is provided by electrical boilers and related consumption concerns mainly to laboratory uses. Artificial lighting sources are incandescent and fluorescent lamps without automated control. Artificial lighting system is responsible for about of 30% of the primary energy end-uses, appliances for 18%, system fans for 5%, system pumps for 7%, DHW production for 12%, and HVAC system for about of 28%.

Fig. 6 shows a trace example of the total power demand and flexible power demand simulated for the "Faculty of Agriculture" building, during a generic working week in the fall season. The trace has been obtained with the usual sampling interval of 5 min. By considering the time series generated for the whole year, we also aggregated some results for characterizing the power demand of different electric systems, called end-use, such as lighting, computers and small equipment, heating/cooling systems, and DHW. Table II shows the peak power demand of each end-use in the four different buildings of the campus.

Finally, Fig. 7 highlights the percentage composition of the electricity consumption for each building over the entire year. In all cases, most of the energy is used for the lighting system. More in detail, in the graduate housing "Santi Romano," lighting accounts for the 66%, the highest observed share. This fact occurs due to the particular use of this building. For the Agriculture Faculty, computer and equipment consumption is higher than for other buildings. With regard to cooling

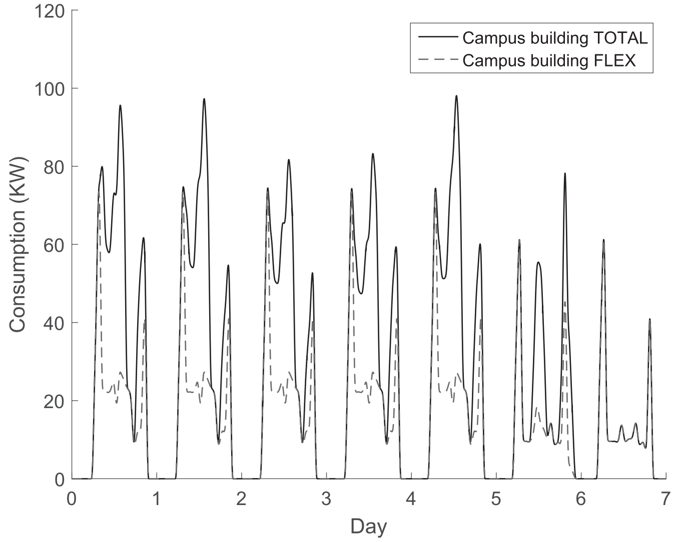

Fig. 6. Power consumption of the "Faculty of Agriculture" building during a generic working week.

TABLE II
ELECTRIC PEAK POWER PER EACH END-USE

	LIGHTING		**COMP+EQUIP**		**HEATING**		**COOLING**		**DHW**	
	kW	**W/m^3**	**kW**	**W/m^3**	**kW**	**W/m^3**	**kW**	**W/m^3**	**kW**	**W/m^3**
Graduate housing	266.8	30.84	182.7	21.81	14.6	1.69	332.0	38.38	0.41	0.05
Agriculture	47.3	0.98	30.9	0.93	91.0		539.6	11.17	-	-
Literature and Philosophy	190.5	7.97	6.1	0.28	-	-	421.3 278.5*	12.35 311.85*	-	-
Biology	102.4	2.34	76.1	3.51	-	-	201.9	4.61	-	-

* Auditorium

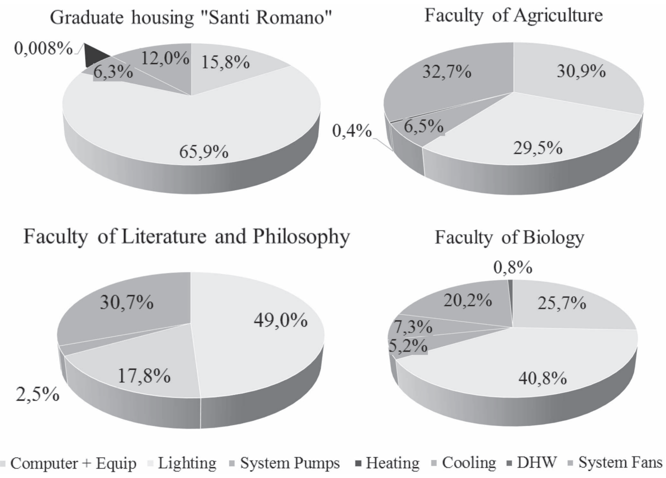

Fig. 7. Yearly electricity consumption composition for each building.

consumption, it must be noted that graduate housing has the lowest percentage values, which refers almost exclusively to the dining hall.

V. OVERGRID EXPERIMENTAL RESULTS

In order to implement the Overgrid service architecture, we developed in Java the software modules responsible of the distributed signaling mechanisms between the nodes described in Section III, by exploiting the open source library for gossip protocols called *JavaGossip* [29], which works on UDP transport packets. We also defined the load control function in another module, which is based on the local estimates of the total power demand and constrain signal sent by the DSO/utility provided by the gossip protocol. The overall service architecture is ready for a deployment on an real system, in case the software modules are connected to the power measuring system and power control actuators available in a smart building.

For testing the correct behavior of the modules and evaluating the Overgrid performance with a real communication network, we emulated the behavior of an Overgrid system, by instantiating multiple virtual machines in our laboratory at the University of Palermo running the Overgrid software modules. Each virtual machine emulates the behavior of a different smart building, by substituting the real power measurements with preloaded power demand traces and the real power control decisions with an output trace of the node internal state. An additional node with a preloaded trace with the power constraints $\mathrm{DR}(kT)$ is also created for emulating the DSO/utility behavior. Although our results are currently limited to a communication network that is basically given by a local area network, the impact of geographic communication networks can be easily tested using, for example, distributed machines available for research purposes in world-wide laboratories [30].

For emulating a significant number of smart buildings, we split the traces described in Section IV week by week (separating winter season from summer and intermediate seasons) in 72 weekly traces with the campus data and 18 weekly traces with the industrial real data. The traces were then used in parallel to compose a network of nodes with, respectively, 72 and 18 independent buildings. The evaluation was carried out by logging every 50 s both the power demand of the nodes and the average power estimate in different experiments based on random network topologies with different connectivity properties, namely, degree $D = 3, 5, 10$.

We assume that the DSO/utility requests apply for time intervals of 15 min. For generating the time series of the power constraints, we considered a wind power generation trace (sampled every 15 min) provided by a European operator [31]. This choice allows us to assess the Overgrid ability to compensate variations in wind power generation.

We first analyze the results obtained with the data from our campus buildings. From these traces, we have simulated 72 nodes with variable power consumption and repeated the experiments for various degrees of network connectivity D. As we will show from the results, the average degree D influences the speed of the P2P system, but has little impact on the ability to meet the requests of the DSO. For easiness of presentation, we report here only a subset of all the experiments produced.

Fig. 8 shows the evolution of the overall power consumption of the 72 buildings with and without DR imposed on the flexible power quota. Fig. 8 shows that Overgrid successfully

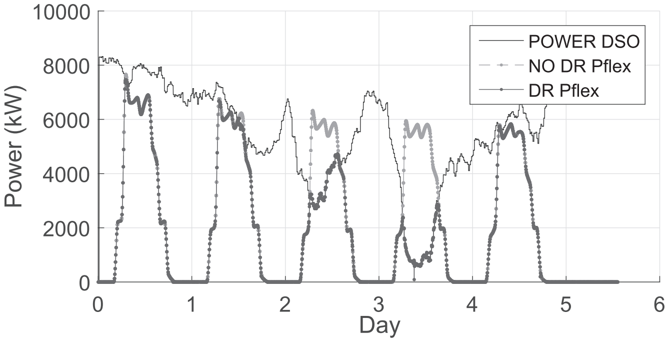

Fig. 8. Power consumption with and without DR for an Overgrid of 72 campus buildings, $D = 5$.

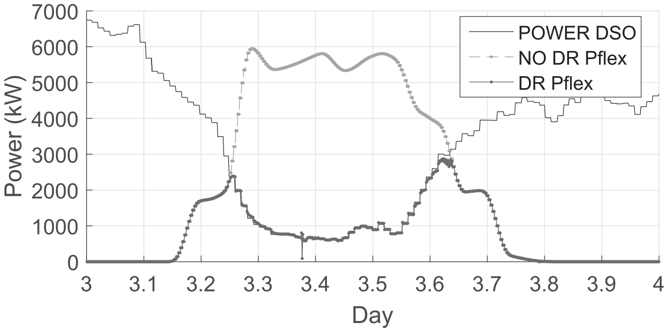

Fig. 9. Power consumption for an Overgrid of 72 campus buildings, detail of day 3.

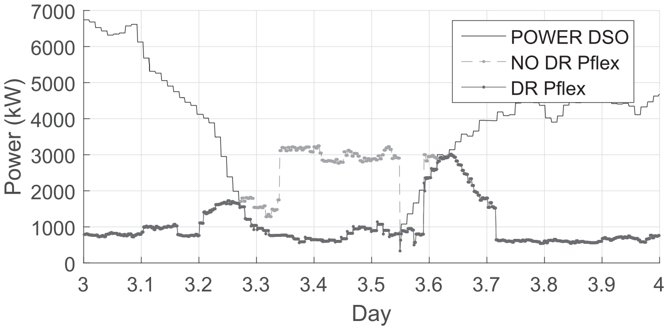

Fig. 10. Power consumption for an Overgrid of 18 industrial sites, detail of day 3.

responds to the DSO/utility requests, even in the presence of sharp changes (e.g., in day 3, from 6 down to 1 MW in less than 5 h). This is better visible in Fig. 9, which shows the detail of day 3 where the DSO variations are most demanding.

The same experiment was repeated with the power trace from the industrial site, emulating 18 different nodes with variable node degree D, and in Fig. 10, we show a sample of the result with $D = 5$ during the same day 3. Form Fig. 10, it is clear that Overgrid is able to correctly respond to the DSO requests of modulating the power consumption.

To assess the performance of Overgrid more quantitatively, we analyzed the "deviations" (relative error) of the total power load against the DSO requests, i.e., when $\sum_{i=1}^{n} \mathrm{load}_i(t) > \mathrm{DR}(t)$. Fig. 11 shows the CDF of these deviations for the campus building traces, while we omit the results obtained with the industrial site trace that are similar. Fig. 11 shows that by choosing as small node degree such as $D = 3$, Overgrid shows no errors at all for over 90% of the time and less than 3% error in about 97% of the cases. This also confirms our simulation results that flow updating works best with small values of D. However, independently from the node degree D, Fig. 11 also suggests that the value of D has little impact on the Overgrid ability to respond to the DSO requests, which performs very well overall, since with higher values of D, Overgrid is still able to track the DSO requests in over 95% of the cases with a maximum error of 10%.

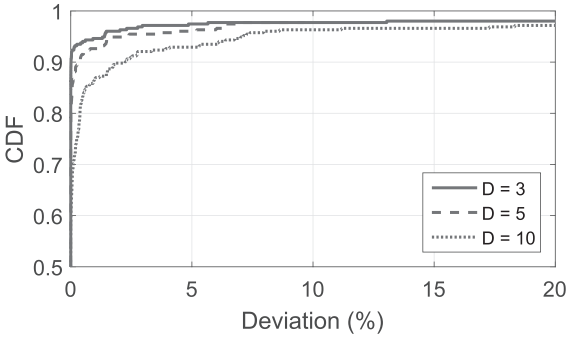

Fig. 11. CDF of the Overgrid deviations from DSO requests.

VI. CONCLUSION

In this paper, we presented Overgrid, a fully distributed P2P architecture designed to automatically control and implement distributed DR schemes in a community of smart buildings. Overgrid is able to control the power consumption of residential buildings, as belonging to a virtual microgrid, regardless of their physical location. In the implementation of Overgrid, we make use of an innovative averaging mechanism, the flow updating, for distributedly monitoring the power consumption of the buildings and the number of nodes in the network. We explored the applicability of flow updating in the Overgrid scenario, using a P2P network simulator, and assessed the performance of this algorithm with realistic power profiles in large networks, with up to 10 000 nodes. We accurately studied the energy characteristics of several types of buildings in our university campus providing some reference models and classifying the amount of flexible energy, the power available for DR programs. Finally, we experimentally validated Overgrid by emulating a real P2P network of smart buildings behaving accordingly to our reference models, demonstrating the feasibility of our approach.

We are currently working on different extensions of our approach for taking into account the possibility to: 1) aggregate buildings with complementary behaviors, capable of operating power consumption modulation all year round; 2) introduce prioritization mechanisms for power reduction; and 3) include storage for improving the integration of renewable source production.

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