Experimental Evaluation of Power Distribution to Reactive Loads in a Network-Controlled Delivery Grid

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***Abstract*—We present experiments with combined reactive and resistive loads on a testbed based on the Controlled-Delivery power Grid (CDG) concept. The CDG is a novel data-based paradigm for distribution of energy in smart cities and smart buildings. This approach to the power grid distributes controlled amounts of power of loads following a request-grant protocol performed through a parallel data network. This network is used as a data plane that notifies the energy supplier about requests and inform loads of the amount of granted power. The energy supplier decides the load, amount, and the time power is granted. Each load is associated with a network address, which is used at the time when power is requested and granted. In this way, power is only delivered to selected loads. Knowing the amount of power being supplied in the CDG requires knowing the precise amount of power demand before this is requested. While the concept works well for an array of resistive loads, it is unclear how to apply it to reactive loads, such as motors, whose power consumption varies over time. Therefore, in this paper, we implement a testbed with multiple loads, two light bulbs as resistive loads and an electrical motor as a reactive load. We then propose to use power profiles for the adoption of the request-grant protocol in the CDG concept. We adopt the use of power profiles to leverage the generation of power requests and evaluate the efficiency of the request-grant protocol on the amount of supplied power. In addition, the deviation of delivered power in the data and power planes is evaluated and results show that the digitized power profile of the reactive loads enables the issuing of power requests for such loads with high accuracy.**

I. Introduction

During the past decades, the North American power infrastructure has evolved into what many experts consider the largest and most complex system of the technological age. However, the vulnerability and potential problems of the power grid has placed the challenges of energy transmission and distribution into the limelight. For example, on August 14, 2003, the U.S.-Canadian blackout affected approximately 50 million people in the U.S. and Canada [1]. A blackout is usually caused by a disconnection of a heavily loaded transmission line that triggers a cascade of imbalances in multiple segments of the grid.

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It has then been of deep interest finding what makes the grid susceptible to such catastrophic failures. The present grid has the property of being perpetually energized. While this property helps ensuring functionality and robustness, it also leads to higher management complexity [2], [3]. Moreover, this property encourages users to access and consume electricity virtually in any amount and at any time. Therefore, it increases both management complexity and the probability of exhausting the existing energy on the grid, and that could eventually trigger blackouts.

Having a permanently energized grid also requires developing complex algorithms to forecast energy demand to keep a timely balance between demand and supply. Close monitoring of the grid's performance may be achieved by deploying parallel (auxiliary) sensing data networks [2], [4]–[12], which in combination with power grid is mostly referred to as the smart grid. However, monitoring alone may not be enough to exercise finer management of the grid.

Therefore, there is a search for a smarter grid where demand is most closely followed by the supply. A tighter grid stability would increase efficiency of the grid by lowering the amount of generated power, and in turn, extending the life of non-renewable energy resources.

Recently, the concept of a controlled-delivery power grid (CDG) has been proposed to achieve a finer and proactive balance between generation of electrical power and the demand of it [13]–[17]. In the CDG, electric energy is delivered in amounts and times as granted by the energy provider on requests issued by users. The CDG may attain a high degree of stability. In this concept, energy is directly supplied as energy quanta to specific user(s) and the delivered amounts are assigned and controlled. Part of this improved management is the result of enabling users (or even loads) to be assigned logical Internet addresses. In order to realize delivery, user's address is tightly associated with the electrical signal. This address, which is an Internet Protocol address, can also be carried by an auxiliary data network [2], [4]–[12]. In this way, energy and the delivery of it are associated to specific addresses.

In a CDG, users issue requests for power and the provider may fully, or partially, grant these requests. Such an approach facilitates the estimation of total users demand and giving the provider the ability to determine how to satisfy the requests by considering energy production, pricing, or prioritization on energy supply. The CDG implies the adoption of a controlled supply even on a feeder with limited capacity.

The concept of controlling the distribution of energy through micro-grids as the next generation electrical grid has been discussed before [18]. Approaches to verify user identification before the transmission of energy starts in point-to-point communications have been considered [2]. However, these analog approaches require one-to-one connection and, therefore, are not scalable when the number of users increases. Some of these works are motivated by the need of incorporating alternative-energy sources into the grid, where sources and appliances may be matched through dedicated lines, using direct current (DC) multiplexors [19]. However, uncontrolled delivery and consumption of energy remains. Another approach to control supplied power involves the adoption of elastic loads. In such an approach, the connection of user loads to the grid is scheduled by the energy provider, leaving the user at the disposition of the provider rather than their own [20].

The use of the request-grant protocol in the CDG requires knowledge of the power profile of a load connected to grid. While resistive loads present a simple power profile, reactive loads present more complex ones. Because plenty of loads, such as motors, home appliances (e.g., refrigerators), general electrical tools, and industrial machines are reactive, the consideration of these loads in the analysis of power distribution is fitting. Therefore, we focus on showing that the CDG feasibly adopts reactive loads through the use of power profiles for issuing power requests (and the corresponding grants) in an experimental setup. However, this method may create a discrepancy between the power recorded by the data exchange through the communication network and the actual supplied power. Herein, we demonstrate that by using an accurate power profile, the power recorded on the data plane of the testbed and that on the power plane is minimized. We refer to power and energy in this paper, with consideration of the timed relationship between power and energy.

The remainder of this paper is organized as follows. Section II introduces the concept of the controlled-delivery power grid. Section III describes the testbed and the models of power usage and collection of data in the experiments. Section IV shows the results of both data and power planes. Section V presents our conclusions.

II. CONTROLLED-DELIVERY POWER GRID

The main goal of a power grid with controlled delivery is to discretize the management and handling of energy on the power grid. The adoption of this approach may enable numerous desirable features on the grid, including minimizing the difference between energy generation and demand, facilitating the power distribution amongst several grids, and increasing the stability of a power grid through local and instantaneous traffic monitoring.

In order to avoid exposing the power grid to discretionary consumption, the electrical signal is associated with the destination address(es) of specific user(s) who are the only one(s) allowed to access the transmitted energy. The destination address(es) may be embedded into the electrical signal(s) or sent through a parallel data network. Figure 1 shows the concept of the CDG using a parallel data network.

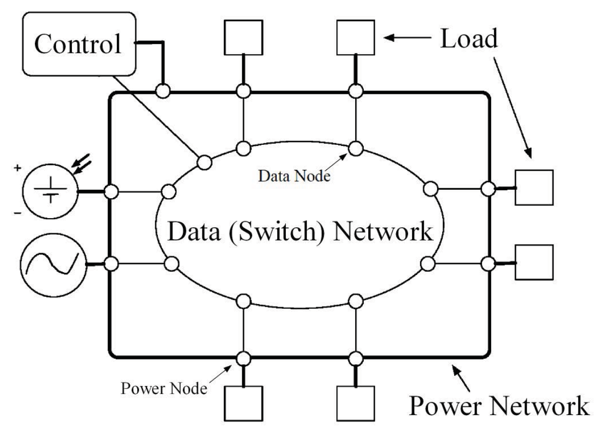

Figure 1. CDG using a parallel data network.

In the CDG, a discrete amount of power is transmitted every time slot. A time slot is the minimum amount of time that power is provided to the user (or load) and this time can be determined by the desired power granularity (in number of watts or in duration of time). This is the time a load is allowed to be connected to the grid per each received energy grant. Consequently, requests are required issued every time slot to keep a load on [16]. The amount of energy per slot may be scaled up in two dimensions: 1) by setting the duration of the time slot, and 2) by setting the amount of energy transmitted within a time slot and adjusting the amount of current for a fixed voltage. In this paper, we use the first approach and a data network for communicating the loads and the energy supplier. The network uses unicast packets as requests issued by users and broadcast packets for grants in the experimental testbed as a simplified approach, where loads and energy supplier are assigned unique IP addresses. In the CDG, the amount of power is set to discrete levels. The selected level of power destined for a user may be controlled by selective current limiters, called smart loads, at the user premises. The energy supplier performs the selection of a smart load by also embedding the amount of current granted per user in the the issued grant.

In the CDG, a control node, or a substation of the grid: a) receives the requested amount of energy issued by users and assigns amounts of it coming from the generation plants to those requests, b) finds routing information about where to forward the energy, and c) appends the destination addresses and the amount of current for the supplied power.

III. CDG TESTBED

We implemented a testbed where the users consume energy for random periods of time to evaluate the adoption of power profiles in the CDG. As Figure 2 shows, there are up three loads, loads 1 and 2 are two light bulbs of 40 and 60 W, respectively. Each light bulb is a *resistive load*, and the load 3 (User 2) is an electric motor; a *reactive load*. Figure 3 is a photo of the motor with a power access point (PAP) used in our test bed. The function of a PAP is to interface the power and data planes of a load by managing the issuing of energy requests and the acceptance of energy grants. This PAP stores the power profile of a load to issue request of the proper amounts of energy needed each time slot. In the testbed, a PAP is implemented on a low-cost computer, Raspberry Pi [21]. The PAP controls a solid-state relay connected to the power line to activate the connected load when power supply is granted. A power profile collected from the AC motor shown by Figure 4, shows that a motor requests a spike of power right after being turned on, and after a small amount of time, the power converges to a fix value (165 W). Therefore, the PAP requests of 370 W during the startup (transient) phase and 165 W thereafter (steady phase) for periods of time determined by the power profile and the time the motor remains on. To mimic a user's actual activity, the light bulbs and the motor are turned ON for periods of time (or continuous time slots).

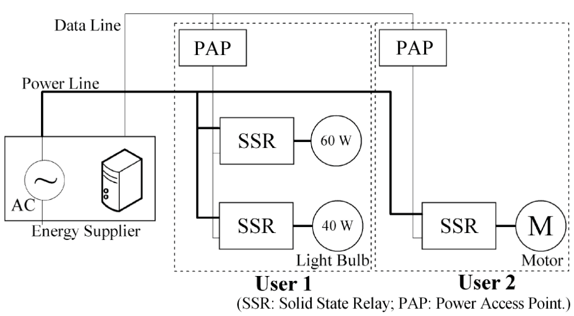

Figure 2. Diagram of the testbed.

The energy supplier in the testbed adopts a round-robin schedule for the selection of users receiving the limited amounts of power. The round-robin schedule provides fairness of service among all users as it follows a predetermined list; the last serviced user has the lowest priority for receiving new service. The two phases of round-robin selection are as follows: 1) Each user issues an energy request, if any, to the distribution point in an allowable discrete amount. 2) The distribution point grants a request if the amount of energy remaining is larger than or equal to the requested level (full supply), or if the remaining energy is larger than or equal to the

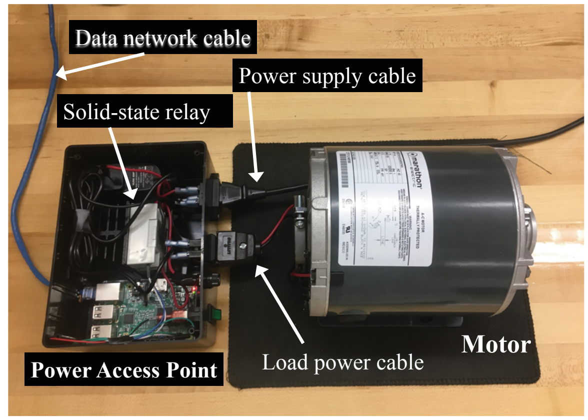

Figure 3. Motor with PAP.

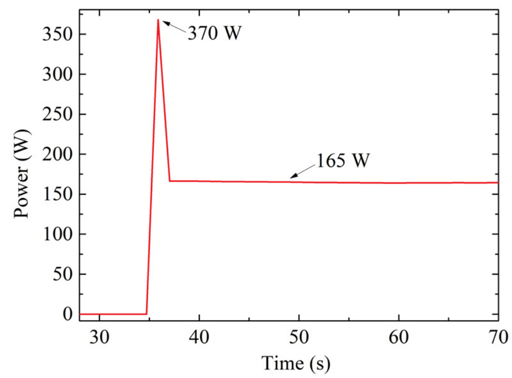

Figure 4. Power requested by a motor during transient and steady stages.

smaller level of energy (partial supply) acceptable by the load but smaller than the original amount of energy requested. Once the remaining amount of energy is zero or smaller than the smallest acceptable level, no more user requests are granted. Energy is supplied in the following time slot after a request is granted.

The energy requests of a user are modeled as a two-state (ON-OFF) modulated Markov process. The energy request that is currently OFF becomes ON with probability q, or remains OFF with a probability 1-q. The request changes its state to OFF with a probability p, or continues in ON state with probability 1-p. In this way, we program the loads to have average ON and OFF periods as determined by p and q. The PAPs generate these requests through a program (executed by the Raspberry Pi, at the user side, and PC, at the supplier side). The energy supplier first fulfills the lower power needs of all users and then moves on to fulfill the next level using the round-robin schedule. Specifically, the distribution node keeps track of the users served and the order in which they are served.

At the time a load is turned ON, the load issues a request for the amount of required power. This amount of power is explicitly described in issued requests. Estimating the amount of required power is simple for resistive loads as this power is constant [16]. However, a reactive load may require additional power at startup and then require a steady amount of power (see Figure 4 as an example). A load may then resort to either using a power profile, where the amounts of power for the transient and steady periods are known ahead of time, or by issuing an estimated amount that includes a possible safety margin. To avoid requesting an overestimated amount of power, we adopt using the power profile of the reactive load in this paper for a real-time distribution of power.

We refer to real-time distribution of electrical power to the continue supply of energy as demanded by a load. Most of today's electrical appliances require this form of supply. In such cases, energy must be provided continuously (for the time the load is ON) as do the loads in our testbed. For example, User 1 may request 0, 40, 60, 100 W and User 2 may request 0, 165, or 370 W. For this, the PAP would generate continuous requests for the period of time the device (bulb or motor) is kept ON. Moreover, we highlight the property of energy routing of the CDG in our testbed by limiting the power capacity of the feeder (distribution loop) so that energy may be designated to users according to a given selection policy. This capacity limit is set at the energy supplier side and users are still allowed to request the maximum amount of power. Continuing with our example, we set the capacity of the feeder to be less than 470 W and show that the feeder may still use the energy on it for a selected load despite not having enough energy to satisfy the maximum possible energy demand. Note that this property is not feasible in the present power grid.

IV. Experimental Results

In our experiments, the power distribution system is capped to 410 W. Therefore, the possible load levels, or the requested and granted power levels, could be $L = \{0, 40, 60, 100, 165, 205, 225, 265, 370, 410\}$ W. For example, if the total amount of power requested by the users is 225 W, the requests are then issued by the 60-W light bulb and the electrical motor which is ON and in its steady phase. Similarly, a request for a 40-W bulb and start phase of the motor as the only requests would be within the cap and, therefore, they would be granted. However, if the 60-W bulb is already turned ON, energy for the motor cannot be granted because its transient-time power demand would be larger than the remaining amount of power in the loop.

We set the PAPs to emulate the behavior of users by setting a self-generated set of energy requests. In the two-state ON-OFF modulated Markov process used in our experiments, the cycle time, T, is set to 300 s and ρ, which is the portion of active period (a load is ON) in a cycle time, is set to 0.8. Therefore, the average duration of the ON state is 240 s ($\beta = \rho T = 240$ s) and the average idle period (OFF state) is 60 s ($\alpha = T - \beta = 60$ s). In the testbed, time is slotted and energy is granted for each time slot. Each time slot, a user selects a discrete amount of energy, with uniform probability, and sends a request to the energy supplier. During an active period, the user continuously issues requests. In response, the provider responds with a grant to each request to keep the load ON. In the same way, the load issues no requests during the OFF time. Other models of request issuance have been also tested [22].

A. Power Recorded on the Data Plane

The energy supplier whose role is played by a desktop PC, which runs the program for selecting requests and issuing grants. This program performs calculations of available power capacity and selection the granted users, and issues data packets for communicating with the PAPs. The issued requests for amounts of power and grants that exchanged between the energy supplier and the users are called data plane. As mentioned before, the time slot has a duration of 300 ms. Therefore, power is requested by the users and granted by the power supplier every time slot. Also, information about the request-and-grant process is collected by the power supplier and PAPs every time slot.

Figure 5 shows the number of requests (bars with vertical blue lines) and grants (bars with horizontal orange lines) issued during a simulation performed for about two hours. As the figure shows, most of the power requested by the loads is granted. However, some of the requests issued by the motor were declined because the 60-W bulb or both light bulbs were ON, therefore, there was not enough power remaining in the loop. Figure 6 shows examples of requested power that is fully and partially granted by the supplier. The black dashed line shows the capacity of the power line, the blue and red lines show the levels of requested and granted power, respectively. As Figure 6(a) shows, only the 40-W bulb is ON before t_1 and the motor requests power at that time. After t_2, both the 40-W bulb and the motor are ON. The requested power is fully granted because the total request doesn't exceeds the power capacity. The time period from t_1 to t_2 represents the transient phase of the motor. However, as shown by Figure 6(b), both the 40- and 60-W light bulbs are ON before t_1, so that when the motor starts to request power at t_1, the power level of requests becomes larger than the capacity. Therefore, the power requested by the motor cannot be granted. Only the light bulbs receive power from the supplier, meaning that power is partially granted.

Figure 7 shows the corresponding requested and granted power. Similarly, the requests issued by the light bulbs may be satisfied all the time. However, because of the cap of the loop, some of the requests issued by the motor are not granted.

B. Power recorded on the Power Line

The total power consumed by the whole system is recorded by a power recorder (*Watts up?*©). The power line using this meter is called power plane in our testbed. This meter records the amount of power consumed by the testbed loads, including current and voltage, in real time. However, this device records one data point per second. Because the power meter collects information about the consumed power, this information can be compared to the granted power for the testbed. Figure 8 shows the number of measure points and measured power

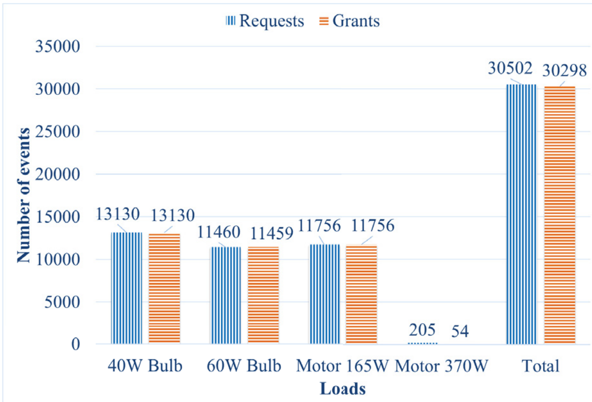

Figure 5. Number of energy requests and grants.

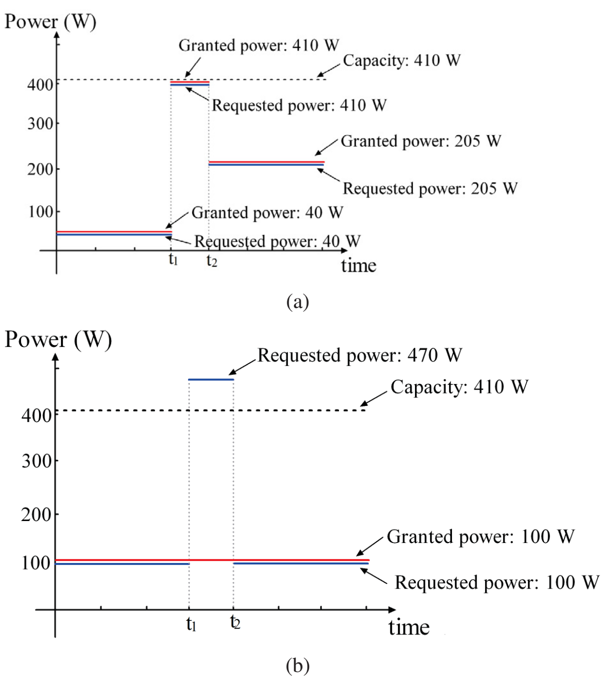

Figure 6. Examples of power requests and grants when (a) power is fully granted to the users and when (b) power is partially granted.

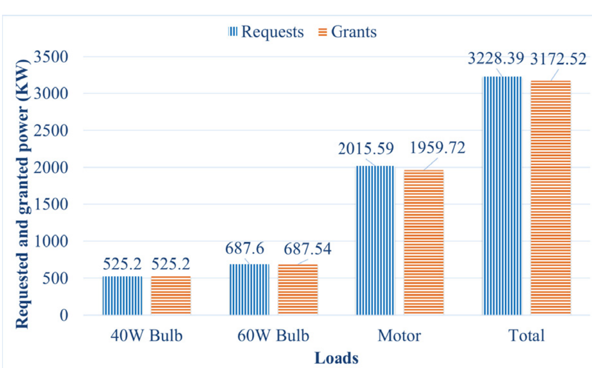

Figure 7. Requested and granted power.

for each power level. However, the aggregated power is used to identify the granted load. For example, if the recorded aggregated power is 225 W, it is easy to identify the 60-W light bulb and the electrical motor as supplied loads. Therefore, after processing the data collected by the power meter, the power granted to the loads can be estimated. Figure 9 shows these loads and the corresponding measured number of grants and measured granted power.

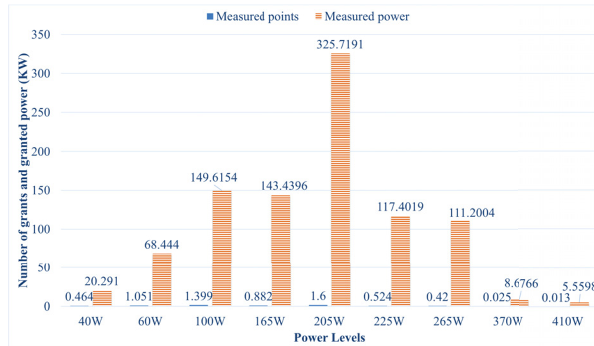

Figure 8. Number of measured data points and measured power for different power levels.

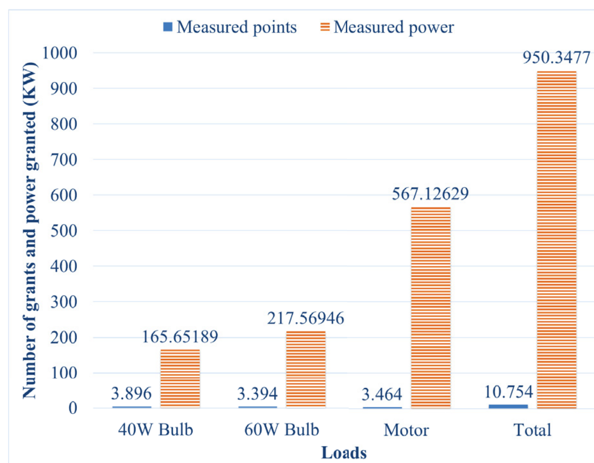

Figure 9. Number of grants and granted power for resistive and reactive loads.

C. Comparison of the Data and Power Planes

Figure 10 shows a comparison of recorded data (granted power) and the power measured. Here, the bars with vertical lines are the recorded data of the granted power from the data collected by the power supplier. The bars with horizontal lines represent the real granted power as calculated from the data collected by the power meter. However, as mentioned above, because the limited number of data points recorded by the power meter, the recorded power is about one third of that recorded from the data plane. Therefore, we multiply the power meter results by 10/3 to obtain the size of the orange bars, which show a similar amount of power as that recorded by the data plane.

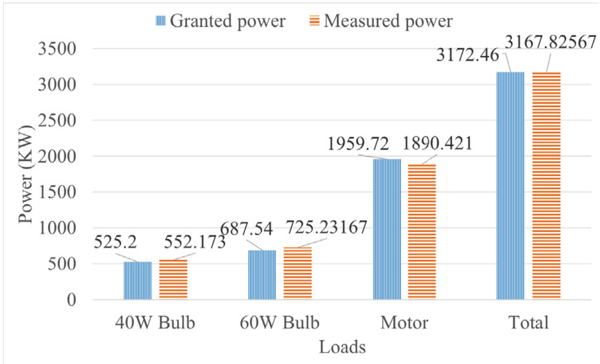

Figure 10. Comparison of granted and consumed power for reactive and resistive loads.

V. Conclusions

We presented a testbed that adopts the concept of the CDG, where energy is addressable and delivery of it follows a request-grant protocol. Each load in the CDG is an independent entity with a network address that may request energy. Therefore, loads in the CDG are practical examples of Internet of Things devices. The CDG uses a data plane, which is information about the power requested and granted, transmitted through a data network running in parallel and managing the distribution of energy through the power line, or power plane. The use of this data plane requires knowing the demand of power at all times a load is on. Although this is simple to implement for resistive loads, the supply of reactive loads calls for the use of power profiles to describe the power demand. For the successful and accurate operation of this approach, the amount of power recorded on the data plane must accurately match the actual power supply on the power plane for accurate supply. Here, we presented a set of experiments with resistive and reactive loads, where the access point of each load determines the request of energy according to the power profile of the load. The reactive load demands different levels of power, including a transient and steady amount of power, that have to be considered by the request-grant protocol. The transient amount of power is larger than the steady amount per time unit for the reactive load. We compared the actual amount of power consumed and that granted in the data plane (through requests and grants). The results showed an accurate match between these two metrics.

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