Allocation of Discrete Energy on a Datacenter using a Digital Power Grid

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***Abstract*—Electrical power supply of datacenters constitutes major operational costs. In principle, two approaches may be pursued in attempting to reduce such costs: 1) optimization of the distribution of computational workload within servers of the datacenter, or 2) by providing the supplying energy to exact match the consumption demands. In this paper, we focus on the second approach by using the properties of a digital power grid. Different from the present power grid, where energy is supplied continuously and in amounts to satisfy large demands, the digital power grid supplies energy in the form of packets and upon request. Energy packets are specifically addressed to one, or multiple servers and to no others, and they carry the amount of energy that has been requested. To evaluate the level of energy supply, we model the consumption time of a server as an ON-OFF Markov chain. Through simulation, we show that the digital grid not only reduces the energy safety margins used by current energy providers to assure system stability, and estimated at 15% above average use, but it also satisfies about 99% of the energy requests of datacenter servers when the capacity of the power grid equals the average energy request and without a safety margin. We also discuss some properties of the digital power grid that integrates data-communications and power equipment.**

***Index Terms*—Cloud computing, Datacenters, Green Cloud, Resource Sharing, Task Scheduling, Carbon Footprint.**

I. Introduction

Datacenters are currently playing an increasingly dominant role of providing Internet services. The role of datacenters has evolved from search engines towards cloud computing services, from which innumerable applications may be derived. Datacenters provide the underlying infrastructure for cloud computing, which offers not only ubiquitous access to information but economical advantages, too; resources may be shared, or rented by a large number of users. Therefore, it subsidizes infrastructure and services.

In order to provide these services, datacenters host thousand of servers in a single or multiple warehouses, and the energy required by the large number of servers becomes one main operational cost.

There has been an increasingly large interest in optimization of the energy demand in datacenters. Optimization of equipment usage is mainly sought, mostly in terms of server and task assignments. A challenge for dynamic allocation of resources is to keep datacenters' infrastructure in stand-by mode with low maintenance costs under low workloads, and switch portions of that infrastructure on as demand increases. In a datacenter, the telecommunications infrastructure, named communication links, switching, and aggregation elements, consume about one third of the total power consumption, while the servers and storage systems consume the remaining two thirds [1]. Therefore, it is important to focus on the energy expenditure of servers as high power consumptions may lead not only to high operational costs, but to thermal hot spots that potentially decrease the performance of the datacenter (and the incurred expenses to related cooling systems) and apparent damages to equipment [2]. A comprehensive evaluation of the energy expenditure of the various equipment in a datacenter has been assessed [3].

Servers and other systems with low utilization may be set to operating states such that power consumption and start-up time are small. This requirement is hard to achieve because of the computing system require a long time to become fully operational (wake up time) from a standby state [4], [5]. Several strategies have been suggested to reduce the number of servers for startup. A method for incorporation of network-traffic management and server workload consolidation has been considered [6]. In this approach, most workloads are assigned to the servers already in use (i.e., on and in active state). Other schemes targeted an indirect detection of power dissipation, e.g., through temperature distribution in the data-center to reduce hot spots and the use of cooling systems [2]. The operation of the servers and the maintenance of cool zones are inter-related as cooling systems exarcerbate the operational costs.

Machine virtualization itself is a strategy that datacenters may pursue for reducing energy costs. Several works on machine virtualization have been reported [7]–[12]. Machine virtualization increases the possibilities of server assignment and therefore, of energy savings [13].

Optimization of the power grid operation is another venue for reducing energy-related costs. By controlling the power distribution to each server, one may save the unused energy when servers are idle on in stand by, while energy is allocated to the more active servers. Furthermore, in cases of distribution loops with high demand surges, protection of the computation jobs (and not only of the equipment) may be dynamically provided by the assigning higher priority allocation of energy to the more critical servers.

However, the presently deployed grid makes these expectations infeasible as this power grid is circuit based: the load, dictated by the maximum expected demand, determines the electrical power supplied, which in turn is disseminated indiscriminately across the grid and amongst the multitude of servers.

A finely-tuned grid is aimed at minimizing the difference

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between supply and demand without compromising the grid stability. For practical reasons, any unused energy in the current grid should be dissipated, else it may damage the transmission lines or the energy source. In order to maintain system stability [14], power providers keep safety margins in a form of over production. Such values vary but are on the order of 15% of the total average power [15]. Furthermore, the flexibility of the energy provider to meet local and temporal demands is limited by the type of generators used and the ease of incorporating them with the power grid. In principal and as implemented today, the over-produced energy may be re-routed to other distribution grids, which face energy shortages. In order to meet such challenges in real time, automated cooperation between grids (including signal phase alignment), and sometimes between competing commercial entities, is required.

Monitoring the present power grids may be achieved by deployment of a parallel (auxiliary) sensing networks [16]–[25]. However, it is still not clear how much efficiency can be increased if the energy supply approach remains the same, where the power in the present power grid is always available and ON to meet a dynamically changing demand. Non-used energy may need to be dissipated to avoid reflections towards the generating equipment, and which is finally wasted [23], [26]. However, computer systems may have proven a different alternative already, showing that a battery can be used to smooth an intermittent energy delivery, as they are commonly provisioned with batteries to overcome energy interruptions or spikes that could re-start the systems and lose information.

The concept of controlling the distribution of energy through micro-grids as the next generation electrical grid has been discussed [27]. The objective of the micro-grid is to increase the efficiency of energy distribution. Approaches to verify customers identification with an address before the start of a transmission of energy has also been considered [23]. However, this requires a one-to-one connection. Therefore, it has limited scalability. Some of these works are motivated by the consideration of alternative-energy sources, where sources and appliances can be matched through separate lines, using direct current (DC) multiplexors [28]. However, the always-ON approach, which is analogous to a circuit-oriented network, continues to be considered in these approaches.

Herein, we propose a different approach to save energy consumption in a datacenter: allocation of energy through a digital power grid. Differently from the current power grid, where energy is supplied continuously and without discrimination of users and usage, the digital power grid supplies packets of energy and on demand.These packets are addressed to a particular or multiple servers. When a server requests energy (based on the server state, e.g., idle or active, and on the level of processing load), a request is made to the energy provider for a precise energy demand. Different from computer networks, an energy packet is of interest to every user, and therefore, it requires security provisions. A packet of energy consists of a voltage (which values indicate the destined address) and an adjustable current delivered by a substation during the packet transmission time. In this way, the digital power grid supplies the requested energy. Therefore, we consider a digital power grid supported by equipment that merges data and power.

To interface the energy provider and the demanding servers, a hand-shake protocol is executed between these two, and packets of energy are delivered to the server. This hand-shake protocol can be adopted in a hierarchical infrastructure, where for example, energy allocation can be implemented within the datacenter power grid and between the datacenter and the energy provider. We consider here, however, a single distribution (hierarchy) level.

Monitoring of the system is assisted by the information provided in the hand-shake protocol, such that in the case of local surges, these are mitigated by local energy storage (batteries or super-capacitors [29]) acting as energy memory. The packets, initiated by server demand, are propagated through the grid, re-shaped, and amplified as necessary through the use of an array of power switches and amplifiers. With a digital power grid, the energy allocated to a particular server is delivered in discrete levels. The fine control on both energy amount and delivery address allows for satisfying a server needs with high resolution. We present scenarios with different discrete levels of energy, including small and large granularity, such that demands and supply are based on these levels. We simulate a digital power grid in a datacenter with a moderate number of servers, and show that the proposed approach decreases the required safety energy margin (from 15%, reported by utility companies) to about 2% for most of the presented scenarios. In addition, we show that a distribution loop with limited energy capacity, the digital grid can accommodate 99% of energy requests when we cap the maximum energy supply to the average of the energy demand.

The remainder of this paper is organized as follows. Section II introduces the digital power grid. Section III presents the performance evaluation of energy allocation on a digital power grid. Section IV presents the drawn conclusions.

II. Packetized Energy Model

The proposed datacenter power grid is based on a basic principle: energy is carried in discrete units, or energy quanta. Each packet carries the amount of energy to satisfy the demand of one or multiple servers. Therefore, the amount of energy carried by different packets may be different. For simplicity, we consider packets with fixed transmission times, each transmission time is called a time slot. An energy packet is sent together with a single or multiple destination addresses, destined to specific servers. To address one or multiple servers, addresses are encoded, such that the address of a single or multiple users can be encoded using a technique, such as code division multiple access (CDMA). Also, we consider that a different amount of power can be provided by varying the amount of current provided to servers (and holding the voltage at a single level), except for providing the destination address(es).

As in the current grid, the generation plants are assumed to have a very slow time response to the second-by-second demand fluctuations. Therefore, the actual demand are shown only at the power distribution points (namely, in real-time) in contrast to the present situation where the demand is forecasted. Such arrangement requires a new switching methodology, whereby a gate-based equipment transmits the constantly produced energy to the digitized grid loops.

The destination information for the energy packets is aggregated and de-aggregated in various parts of the digital grid. Furthermore, control over the various nodes may require an auxiliary network (data network) which carries the energy requests from the nodes and ascertain the arrival or the energy packet to its destination.

We refer to the part of the grid that carries energy as the power network, and the part of the grid that carries information as the data network. A data network, used for partial control of the transmission of energy, is integrated into the network for the transmission of energy. The digital power grid can be subdivided into different segments: long-haul, regional, and local segments. The functions of each segment of the packetized grid are summarized as follows: 1) A long-haul segment carries information and power between the power source (whether a generation plant or a substation) and the regional segments. 2) A regional segment allocates energy among the local segments and collects the aggregated energy requested by servers (at the local segments). 3) A local segment sends the packetized energy addresses to specific servers. The different segments, or a partial model, may be followed by the electrical grid of a datacenter. Servers send their energy requests through this segment, and each request may include the requested amount and the server's address. Energy can be targeted to servers via either a shared distribution loop (or broadcast media) or a point-point distribution loop.

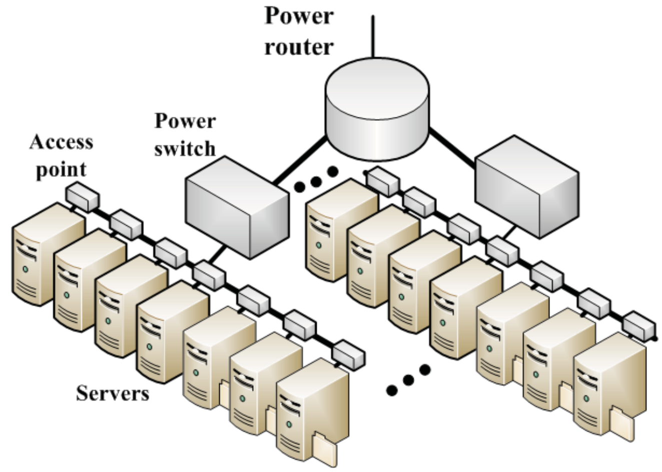


Fig. 1. Different interconnection equipment in the digitized grid.

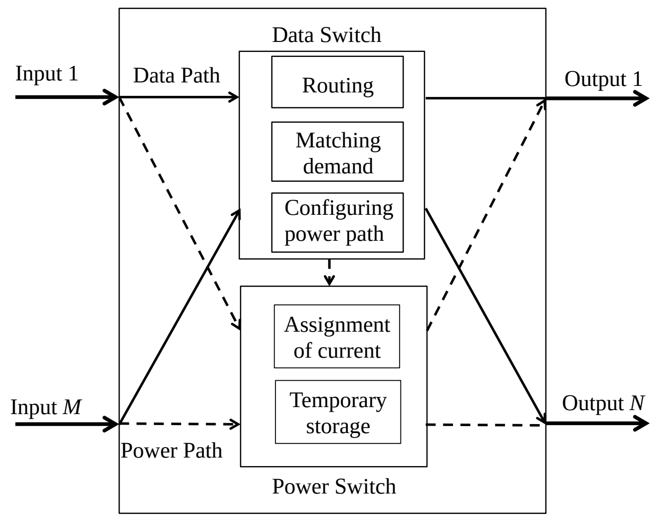


Fig. 2. Architecture of a power switch.

A. Network Elements for the Digital Grid

The different equipment used for the digital grid forward energy packets toward the servers after analyzing the destined address, which is provided by the local distribution substation. The array of nodes along the distribution segment receive the energy packets, decode the addresses and forward the packets to the proper destinations according to a determined end-to-end route. This digital-grid equipment is coarsely divided into three categories: *power router*, *power switch*, and *power access point*. Figure 1 shows the different components in their placement at various part of the digital power grid.

The grid equipment of the digital grid represents a fusion of power electronics and computer networks, where power electronics are used to transmit energy packets to destined server. The data path of the nodes in the digital grid a) finds the requested energy levels as issued by servers (or local distribution points) and assigns the incoming power to supply those requests, b) finds routing information about where to forward the energy, and d) attaches destination information and information about the supplied energy for secure and guaranteed delivery. Because energy quanta (i.e., each quantum) is the same for each destination (in terms of a single unit), the switching function does not need to differentiate the incoming energy but the outgoing one, in a destination-server basis.

The function of digital-grid equipment is summarized as follows: *Power routers* interconnect long-haul and regional segments, and segments from local loops under different administrations (e.g., utility companies), with the purpose to route energy to alternative local segments or from different generation plants. They perform routing between these two ends, energy sources and servers. Alternative-energy sources can be considered as small power generation plants. Figure 2 shows a possible architecture of a power router. The power routers comprise a power path, through which energy is delivered to servers, and a data path, which transmits the information to monitor server demand and supply and to configure the power paths. The inputs and outputs of power router receive data and energy packets, they are processed internally through different paths and merged again at the egress side of the switch. The inputs and outputs can use shared or dedicated transmission lines. A shared line means that the high voltage to transmit energy carries the data information embedded in it. Dedicated lines means that energy and data use one line separately (e.g., data lines could use optical fibers). A *power switch* interfaces local and regional and local distribution lines. It also aggregates energy request from local segments and forwards them to power routers. A *power access point* provides server access to the digital power grid. The power access point collects requests of energy, communicates with the power switch (at the substation) to request energy and direct the energy to the server. The power access point also serves as a security device to identify and authenticate the addressed server. It also monitors the amount of current drawn by a server (similar approach as in the CW grid [30]).

B. Scheduling Energy Service to Servers

An actual energy loop has limited capacity (C, where the capacity is the maximum amount of energy that can be delivered to servers in a time slot), and there could be periods of time where the energy demand may be larger than the available capacity. It is of interest to show that the digital grid is capable of handling the distributed of the limited energy. This capacity may be used to indicate the largest number of servers in the datacenter or the computing load that can be actually provided by the datacenter, even in the scenario where the demand is much higher than the loop capacity. In a case like that, the CW approach would fall short of satisfying a single server as all the energy would only be dissipated among all servers connected to the distribution loop.

In this paper, we aim to provide a fair share of energy supply to the different servers connected to a distribution loop in the digital power grid. We then select a *round-robin* service policy, which is described as follows:

Step 1. Servers with energy demand send their request to the corresponding power router, while energy is needed (each request is for one time slot).

Step 2. The power router receives all energy requests and selects servers that can be served (by considering the amount of energy requested and the capacity of the grid) in a round-robin fashion, encodes the granted server addresses and sends the energy packets in the next time slot. The power router keeps a pointer indicating the following starting point (server) to be served in the next opportunity.

Step 3. Repeat to the first step as long as there is a server requesting energy.

III. Performance Evaluation of the Digital Power Grid in a Datacenter

We simulated the energy distribution in a datacenter using the proposed digital power grid. The energy demand of a single server is modeled by using an two-state-modulated (ON-OFF) Markov process. In this model, a server that is currently OFF becomes ON with probability q, or remains OFF with probability $1-q$, for one hour (other durations are also feasible and the results would show similar trends as those presented in this section). At the beginning of the following hour, the server changes state to OFF with probability p or remains ON state (for one hour) with probability $1-p$. This model allows us to approximate the actual (energy) bursty demand of a larger number of servers.

We study a case where there are 1000 servers requesting energy at random times (ON-OFF model) and with bursts of different average durations. As we have a digital grid, where the amount of power delivered to a server can be finely specified, we consider that the energy demand is also discrete. The discrete amounts of power can have a single or multiple numbers of watt-hours. Table I shows the 15 different scenarios (numerated from 1 to 15) considered in our study. The scenarios differ in the number possible levels of energy and amount of energy per level that a server may request. The digital power grid then attempts to satisfy the levels of energy requested. However, if the power grid cannot provide a requested energy level (because of exhaustion of the energy capacity) it then attempts to provide a smaller level of energy. For example, in Scenario 2 in the table, the energy levels that can be requested are 3 and 6 units. If a sever requests 6 units, but the power grid is not be able to provide those, it may provide 3 units if available. Note that this scenario cannot be accommodated by the current electrical grid infrastructure as energy is not addressable and all servers connected would consume whatever is on the distribution line.

Furthermore, the server energy request is modeled by providing a probability that a level is requested for each server. The table then shows the probabilities for each possible energy level in each scenario, in the third column. We explore the cases when the probabilities for each level request are the same and different.

As we are interested in minimizing the total amount of energy required to energize a complete datacenter, we consider a scenario where the distribution loop has a capacity equal to the average consumption of energy. This is, we focus on minimizing the additional amount of energy prodded to satisfy sudden energy surges as those are expensive to provision for and most likely occasional. Therefore, the energy capacity is estimated as the average energy request for about 3 years, where a day is divided into three periods of 8 hrs each, where the periods have an average (burst) request of 3, 6 and 9 hrs, and requests can arise in an ON-OFF Markov modulated process in hourly basis.

A. Results

Figure 3 shows the amount of requested energy of 1000 days and the amount of provided energy, for all 15 scenarios. The figure shows that the cases with a small number of levels may average small average energy request while those with a large number of levels, the average energy request is high. Furthermore, the results show that in every scenario, the average energy supplied is very close to that requested.

Because those amounts are small, Figure 4 shows the differences between the requested and supplied energy of the considered scenarios. The figure shows that for Scenarios 1 to 12, the discrepancy is equal or smaller than 2% and the larger case is for Scenario 15, where the discrepancy is 7%. This is a significant reduction of the energy margin, as it is currently reported to be 15% by utility companies.

Because the digital power grid not only reduces the energy margin required to satisfy occasional and spiking energy demands, but also eliminates this margin as it can allocate the available energy selectively. Therefore, it is important to

TABLE I
TEST CASES FOR DISTRIBUTION OF ENERGY IN DIGITAL GRID

Scenario	No. of levels	Levels	Prob. of per level
1	1	3	1
2	2	3, 6	0.7, 0.3
3	2	3, 6	0.5, 0.5
4	4	3, 6, 9, 12	0.25, 0.25, 0.25, 0.25
5	4	3, 6, 9,12	0.1, 0.2, 0.3, 0.4
6	4	3, 6, 9,12	0.4, 0.3, 0.2, 0.1
7	4	1, 2, 4, 8	0.25, 0.25, 0.25, 0.25
8	4	1, 2, 4, 8	0.1, 0.2, 0.3, 0.4
9	4	1, 2, 4, 8	0.4, 0.3, 0.2, 0.1
10	8	3, 6, 9, 12, 15, 18, 21, 24	0.125, 0.125, 0.125, 0.125
11	8	3, 6, 9, 12, 15, 18, 21, 24	0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.3
12	8	3, 6, 9, 12, 15, 18, 21, 24	0.3, 0.175, 0.15, 0.125, 0.1, 0.075, 0.05,0.025
13	8	1, 2, 4, 8, 16, 32, 64, 124	0.125, 0.125, 0.125, 0.125
14	8	1, 2, 4, 8, 16, 32, 64, 124	0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.3
15	8	1, 2, 4, 8, 16, 32, 64, 124	0.3, 0.175, 0.15, 0.125, 0.1, 0.075, 0.05,0.025

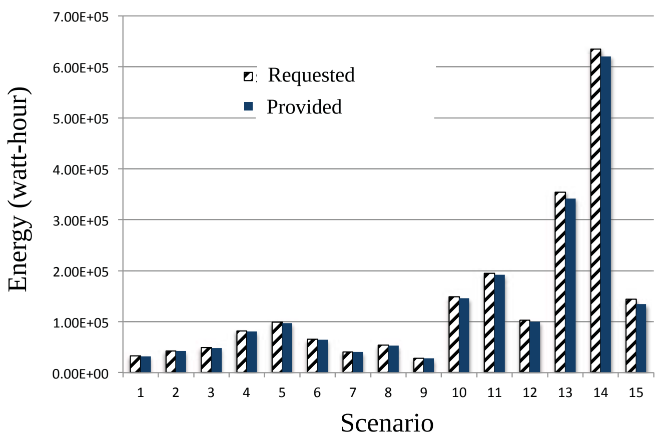


Fig. 3. Requested energy and supplied energy.

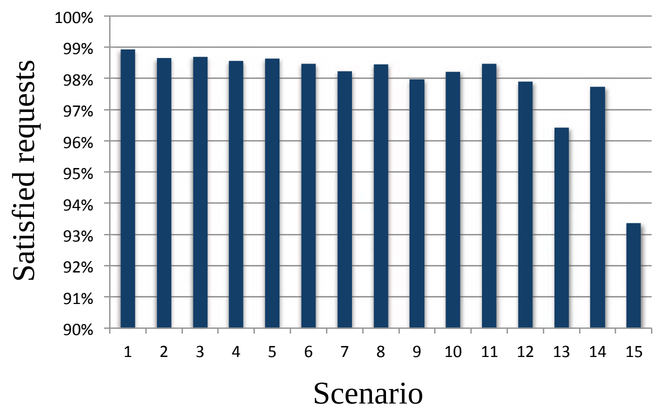


Fig. 5. Percentage of satisfied requests.

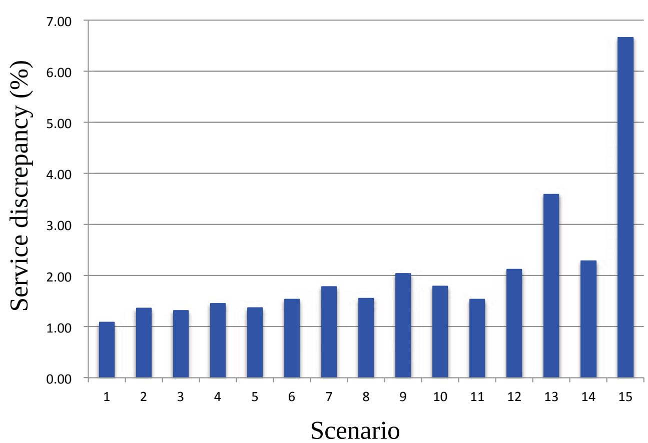


Fig. 4. Difference between requested energy and supplied energy (watt-hour).

estimate the number of requests that are fully satisfied. Figure 5 show the percentage of fully satisfied requests. As this figure shows, Scenario 15 received 93% satisfaction, Scenario 13 received 96% satisfaction and the remaining scenarios received above 99% satisfaction.

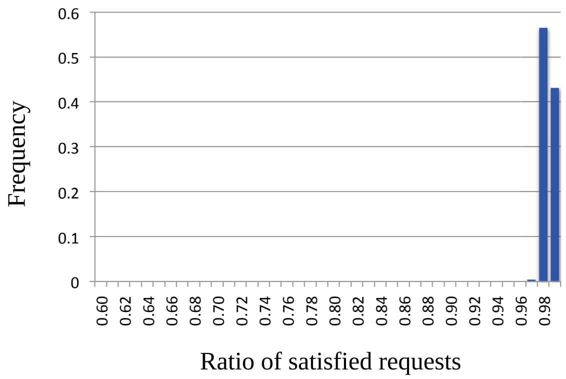
Figure III-A shows the distribution of satisfied requests for Scenarios 1 and 15. Scenario 1 has the highest percentage of satisfied request and Scenario15 has the lowest. As the figure shows, the distribution of satisfied request is highly concentrated around the average in both scenarios. This indicates that the service is fair and similar for most servers.

IV. CONCLUSIONS

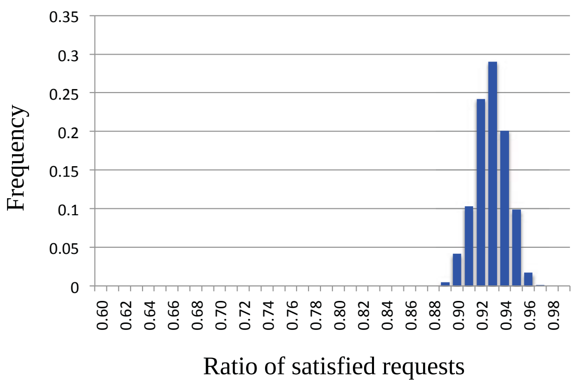
In this paper, we presented a digital approach to the power grid for a datacenter. This paradigm sends energy in packets to different and specific servers in a datacenter. The implementation of the digital grid would require the addition of power equipment that can decode server addresses and communicate with the substation supplying the energy.

The performance gain obtained with the proposed approach is presented as minimization of energy margin required to satisfy large energy demands. Furthermore, in the case where energy capacity is smaller than the sporadic demand surges required by a datacenter, the distribution of energy can be handled selectively. We studied cases with requests with different energy levels, modeled as ON-OFF Markov modulated processes, and showed that the levels of satisfaction are higher than 99% for most scenarios. The worst case scenario was 93%. In all these cases, we show that high energy demands can be controlled by the digital power grid.

Furthermore, as servers in a datacenter may be assigned different workloads, it is expected that each server may have different energy demands. The proposed approach can be used to cross-layer optimize computing jobs assignment and energy supply for efficient datacenters.



(a) Distribution of Scenario 1



(b) Distribution of Scenario 15

Fig. 6. Ratio of satisfied requests (those requests that have been fully satisfied). (a) Scenario 1 and (b) Scenario 15. In both cases, the values are highly concentrated around the mean.

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