measure energy consumption

The evolution of cloud computing which provides on-demand provisioning of elastic resources with pay-as-you-go model has transformed the Information and Communication Technology (ICT) industry. Over the last few years, large enterprises and government organizations have migrated their data and mission-critical workloads into the cloud. As we are moving towards the fifth generation of cellular communication systems (5G), Mobile Network Operators (MNO) need to address the increasing demand for more bandwidth and critical latency applications. Thus, they leverage the capabilities of cloud computing and run their network elements into distributed cloud resources.

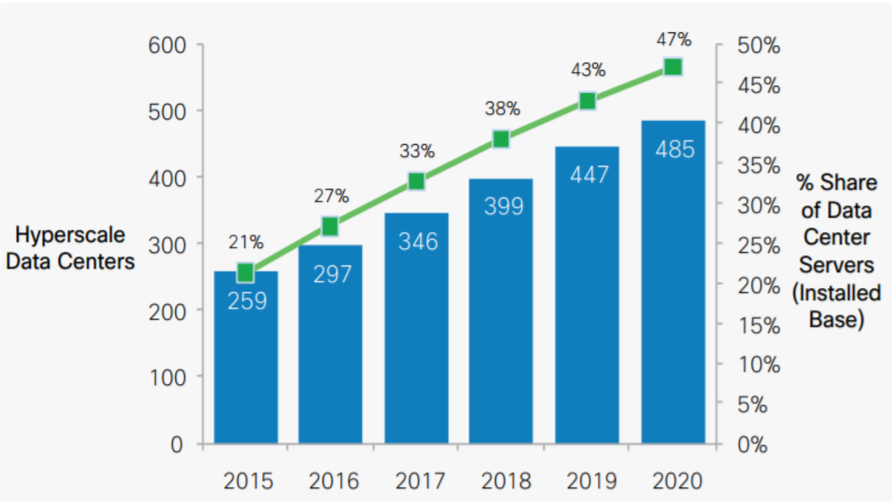

Fig. 1 Growth of hyperscale data centers by 2020 [1].

The adoption of cloud computing by many industries has resulted in the establishment of humongous data centers around the world containing thousands of servers and network equipment. Data centers are large-scale physical infrastructures that provide computing resources, network and storage facilities. Cloud computing is expanding across different industries and along with it the footprint of data center facilities which host the infrastructure and run the services is growing. Since 2015 there has been 259 hyperscale data centers around the globe, and by 2020 this number will grow to 485 as shown in Fig. 1. These type of data centers will roughly accommodate 50% of the servers installed in all the distributed data centers worldwide [5].

Data centers are promoted as a key enabler for the fast-growing Information Technology (IT) industry, resulted a global market size of 152 billion US dollars by 2016 [2]. Due to the big amount of equipment and heavy processing workloads, they consume huge amount of electricity resulting in high operational costs and carbon dioxide (CO_2) emissions to the environment. In 2010, the electricity usage from data centers was estimated between 1.1% and 1.5% of the total worldwide usage, while in the US the respective ratio was higher. Data centers in US consumed 1.7% to 2.2% of the whole US electrical usage [3]. Fig. 2 shows that over the past few years, data center's energy consumption increases exponentially.

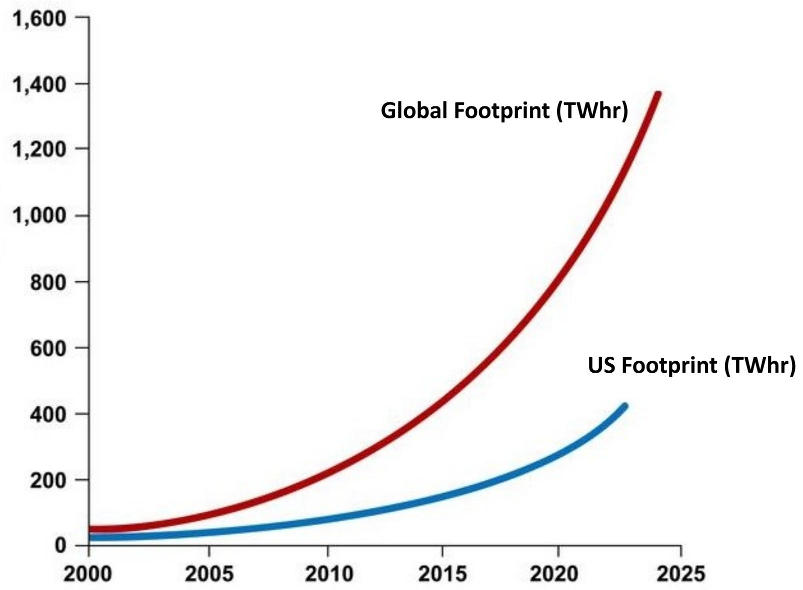

Fig. 2 Projection of data centers' electricity usage [4].

Objective of the thesis

As discussed in the previous section, the number of data centers increases and so does their respective electricity usage. There has been increased interest from data center's vendors and operators as well as from the academia, to understand how the energy is consumed among different parts of the data center's infrastructure. A wide body of the research is focused on modeling and prediction of energy consumption. The majority of studies [2] is focused on the energy consumption of the computing subsystems such as servers, network plane and storage, while there are also studies on the energy usage from mechanical and electronic subsystems such as computer room air conditioning (CRAC) units.

This work is focused on the energy consumption of the server, which belongs to the data center's IT infrastructure. Understanding how the energy is consumed among the components of the server is essential to define an energy prediction model. This thesis presents a system-level power model of the server, which includes the power consumption of the processor, the random-access memory (RAM), and the network interface controller (NIC).

The model is based on Lasso linear regression [67] with non-negative coefficients. The selected variables reflect the power consumption activity of each hardware component. The model is independent of the usage of the server. The test cases are created in a way to explore all the possible workloads of each hardware component. The data collection includes the regression variables as well as the power consumption associated with each measurement. We used regular approach for dividing our data set into training, testing and validation sets. The model which is derived after fitting the data with the training set, is tested for its prediction accuracy against the testing set. The validation set which is a random sample of the data collection, is used afterwards to evaluate our predictions against data which is unknown to our prediction model.

This study, demonstrates the feasibility of deriving a system level power model that can be applied for predicting the energy consumption of the server without using any available tool or utility. We show the advantage of using L1 regularization for reducing the number of coefficients in regression-based power modeling. We also provide a power model that is independent of power usage scenarios and which can be used for run time power estimation with reasonable accuracy.

Structure of the thesis

The thesis is structured into five main chapters starting with the introduction of the topic. The rest of the work is organized as follows:

Chapter 2 gives an introduction on data centers energy consumption, and briefly presents the architecture of data center. It explains the importance of energy consumption modeling and prediction, and describes how they are used to increase the energy efficiency in different areas of data center such as computing resources, network plane, virtualization layer and associated business cases. Finally, it presents power modeling and prediction approaches in processor, server and data center levels.

Chapter 3 presents the regression based power model that we use to construct the equation which predicts the energy consumption of the server. It describes the regression variables that are used during the model fitting and explains the methodology followed for deriving the model.

Chapter 4 describes how the experiment is set up. It presents the characteristics of the server which is used for data collection, and the tools that we developed and used to collect the data. The test cases which are created to cover all possible workloads are also presented in this section. Then it explains the steps which are done for fitting the model and presents the final power model. Finally, it explains the model evaluations, and illustrates the results for the accuracy of the model in different server's workloads.

Chapter 5 summarizes the work briefing the purpose of constructing the energy model for the server. It states few observations about the regression variables that are used and the results that we got. Finally, it and proposes alternative directions that could result in more accurate predictions and would test the adaptability of the model in different types of servers.

Data center energy consumption

Data centers typically are powered by electricity. However, following the strategy for decreasing carbon emissions and complying with sustainable operational models, modern data centers use alternative energy sources such as geothermal, wind and solar power. The electric power flows from external power grids into internal infrastructure facilities, Information Technology (IT) equipment and other support systems. The energy flows to the internal IT facilities through Uninterrupted Power Supplies (UPS) to maintain a consistent power distribution even during possible power failures.

The architecture of a data center is complex since it does not only consist of the hardware elements but also the software that runs in the IT infrastructure. Therefore, we can categorize its elements into two layers which are hardware and software, as shown in Fig. 3. The hardware consists of many components. The major ones are cooling systems, power distribution units, lighting equipment, servers and networking equipment. The software layer can be further divided into two subcategories, the Operating System/Virtualization layer and the applications. The first mainly refer to the host OS that is installed in the servers and the cloud deployment running on top of it. The second refers to the different type of applications running in the servers which vary depending on the industry and business cases.

Understanding how the energy is shared among the elements of such a complex system as well as predicting energy consumption, requires a system optimization cycle as presented by M. Dayarathna *et al*. in [6]. Whether we want to model the consumption of the whole data center or we are particularly interested in the IT infrastructure, the general approach can be narrowed down to the following process. Initially, we need to measure the energy consumption of each component that is considered and identify where the most energy is consumed. For that we select the features that will construct the power model. Different techniques can be used for feature selection, such as regression analysis and machine learning. The accuracy of the power model needs to be validated. Finally, the model can be used to predict the system's energy consumption, and find out means to focus on improving the energy efficiency of the data center.

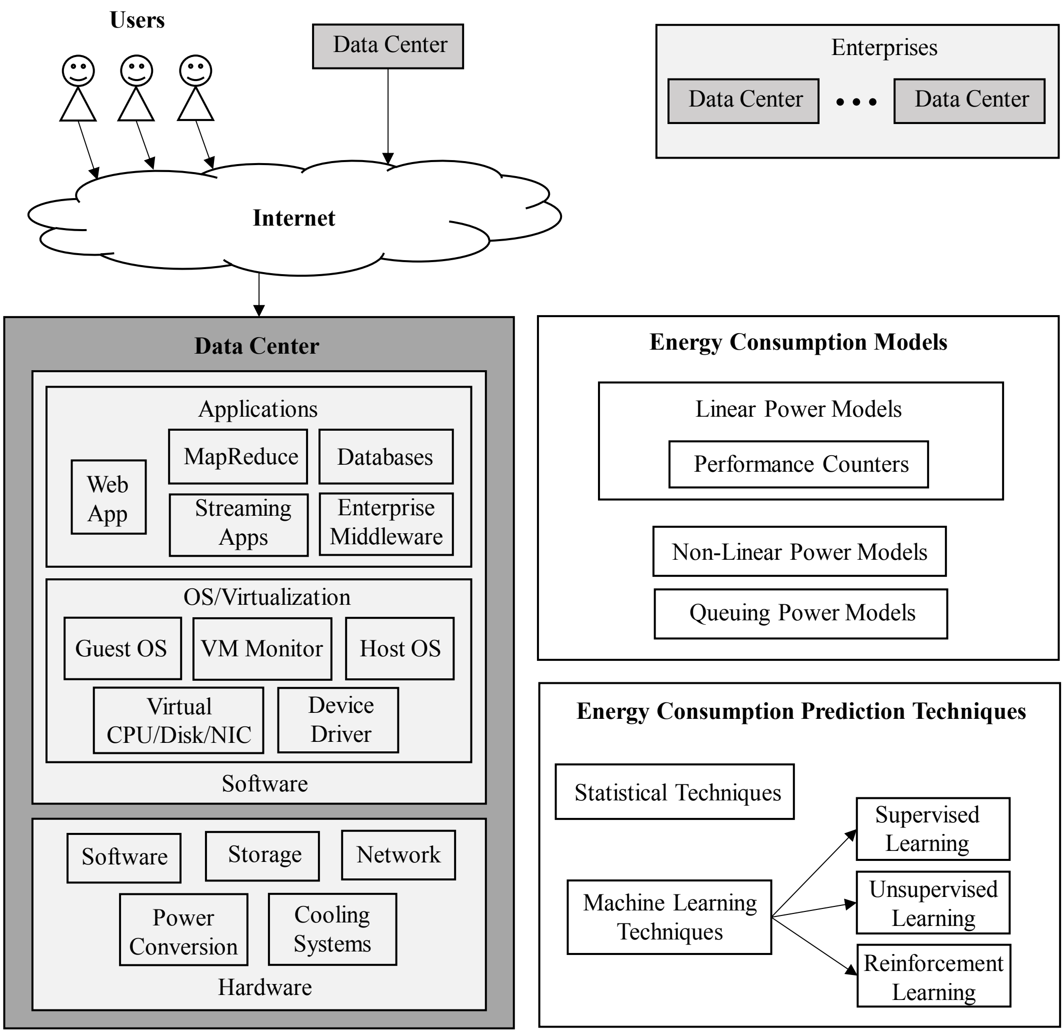

Fig. 3 A view in the context of energy consumption modeling and prediction in data centers. The components of a data center can be categorized into two main layers: software and hardware.

There has been a lot of research on energy consumption prediction for data centers Information Technology infrastructure. Initiatives and efforts to reduce the cost associated with the power distribution and cooling of the equipment are expanding, hence the power management has become an essential issue in enterprise environments. Server takes the highest chunk of the energy consumption in the racks [6]. Consequently, there is need of understanding how the energy is consumed and what are the main components of the server which impacts the energy consumption the most. Several studies [57][59] evaluate the system level power consumption and propose models which predict the energy considering various server components. Other studies [43][50][54][55] focus on processor's power consumption. The processor is the component inside the server which consumes the most energy.

Hardware Performance Counters are proposed in many works [43][50][55] to estimate power consumption of any processor with the use of data analytics or statistical techniques. They provide significant information about the performance of the processor. The event counter mechanisms have different implementation which varies depending on the processor family, and so does the number of the available software and hardware events. Also, there are limitations on how many events can be measured simultaneously. For example, the IBM Power 3-II has 238 available performance counters, while only 8 of them can be measured simultaneously [7]. In the Intel Pentium II processor, only 2 events out of 77 can be measured concurrently [7].

Towards a green data center

There are many best practices and guidelines for achieving energy efficiency in the data centers. Nevertheless, the over-provisioning of IT resources leads to underutilized IT equipment and energy inefficiency. It is accepted that low utilization of servers, inefficient network plane management, limited virtualization adoption, and lack of business models [8] are the most significant factors that impact negative the energy usage cause by IT loads. In this context, we present solutions which try to tackle these challenges and make data centers greener.

Server Plane

Google stated that a typical cluster of servers is utilized on average 10% to 50% [9]. Dynamic power management (DPM) has been proposed to address the energy inefficiency cause by underutilized servers. Dynamic voltage and frequency scaling (DVFS) is one technique for DPM which uses low voltage supply and low frequency. When there is not intensive work load in the server, neither is need to operate a processor at maximum performance [10]- [12] we can apply DFVS to save energy. Another approach is server consolidation. We consolidate jobs to a limited number of highly utilized servers, and switch the rest into low power or OFF states [13]- [17]. Job scheduling is also used to improve workload management focusing on energy conservation to achieve higher server utilization [18]- [20].

Network Plane

These studies [21]- [23] estimate that network infrastructure consumes 20% to 30% of the total energy consumption in a data center. Network links are highly underutilized, operating between 5% and 25% [24], and they remain idle for approximately 70% of the time [25]. K. Bilal et al. [26], explain that the conventional three-layer tree topology consumes significant amount of energy, partially because enterprise level devices consume a lot of electricity. Alternative data center topologies, such as Fat-Tree [20], Jellyfish [28] and VL2 [29], are proposed to tackle the energy inefficiency of the conventional topologies.

Virtualization techniques is another approach for better network resource utilization. Software defined networking (SDN) solutions provide dynamic resource allocation [30], and network resource scalability by adjusting the active network components of the data center [31]. Network load and energy consumption proportionality is another factor that impacts the energy consumption in the data center networks. Network devices remain underutilized; however, they consume significant amount of energy. D. Abts et al. [32], present methods that adjust the power consumption and the performance of the network based on the amount of traffic. C. Gunarante et al. [33], show that Adaptive Link Rate (ALR) in Ethernet links can maintain a lower data rate for more than 80% of the time, saving significant energy and only adding a very small inflation to the delay. The conventional tree topology or the strictly adoption of bisection topologies such as VL2, Fat-Tree and Jellyfish, are not separate solutions towards an energy efficient network plane. Data centers run different type of applications and services.

A holistic design and common approach for a specific topology does not benefit neither the quality of services nor the operation of the data center. There is need for application-specific solutions that suit the dynamics of the modern data centers and allow flexibility in energy utilization management, improving the efficiency [34]. SDN and virtualization techniques are undoubtedly game changers when reshaping and optimizing the network infrastructure. These technologies allow us to adjust the operation of the network plane based on the network load which yields remarkable amount of energy consumption. Disruptive evolution of data analytics and machine learning can provide meaningful information to the data center operators. They can predict the traffic and adjust the behavior of the network elements according to the demand, without compromising the quality of service (QoS).

Virtualization Plane

One of the benefits of virtualization is that we can share the available physical resources among virtual machines (VMs). Dynamic resource allocation is a technique which allow us to utilize and assign dynamically free computing resources among VMs, saving at the same time considerable amount of energy. Virtualization is an efficient way to provide server consolidation and power off the server that operate in idle mode. In many cases, an idle server consumes 70% of the power consumed by a server running at the full CPU load [35].

Business Model Plane

Lack of proper business models, pricing policies and conflicting priorities, are additional reason for creating energy inefficiency. Customers are not charged in proportion to their resource utilization. The lack of monetary agreements between data center owners and customers increases the interest towards an environmental chargeback model that charges tenants based on their energy consumption [36]. Microsoft has implemented such chargeback models where customers are charged according with their power usage [37].

An alternative approach that can help businesses to adopt energy practices is the collection of metrics related to energy consumption. There are various metrics which allow us to measure infrastructure energy efficiency. The Green Grid consortium has proposed Power Usage Effectiveness (PUE). It defines the ratio of energy that is consumed for cooling and power distribution of the IT infrastructure, to the energy used for computing. PUE closer to 1.0 means nearly all the energy is consumed for computing. Often PUE does not consider all the elements of the IT infrastructure, hence it adequately reflects efficiency [38]. There has been effort to redefine the metrics that measure the energy efficiency in a better context such as power to performance effectiveness (PPE), data center productivity (DCeP), and data center infrastructure efficiency (DCiE) [38], [39].

Architecture of cloud infrastructure and multitenant virtualized environments of data centers increase the complexity of the chargeback models. Resources are shared and therefore chargeback models that incorporate flexible pricing models must be developed. There are initiatives to integrate such models with cloud infrastructure and data analytics. One example is Cloud Cruiser for Amazon Web Services [40].

Processor level power modeling

Processor is one of the largest power consumers of a server [41]. It has been shown that the server power consumption can be described by a linear relationship between the power consumption and CPU utilization [42]. There are many comprehensive power models that rely on specific details of the processor architecture and achieve high accuracy in terms of processor power consumption model. This section, describes different studies on modeling and predicting power consumption using performance counters and associated events, in processor level. These models, applied during thread scheduling and Dynamic Voltage/ Frequency Scaling (DVFS) configuration.

Rodriges *et al*. [43] estimate power consumption in real time by exploring microarchitecture-independent performance counters. They use two different CPU cores, one suitable for low power applications and another for high performance applications. Their study considers a small set of events and associated counters that have strong impact to the power consumption. These variables are available in both types of cores and are obtained from [44]. Super ESCalar Simulator (SESC) [45] is used for simulating the architectural performance, and Wattch [46] for monitoring the actual value of power consumption. 8 benchmarks are selected from SPEC [47], MiBench [48], and mediabench suites [49], to test the variables for both types of cores. The correlation between each variable and power consumption is computed by using the Pearson's correlation formula.

Their results show a high correlation among Fetched instructions, L1 hits, IPC, Dispatch Stalls and retired memory instructions, indicating a power estimation across multiple types of architecture with an average prediction error of 5%.

Singh *et al*. [50] propose Performance Monitoring Counters (PMC) for power consumption estimation using analytic models. They use perfmon utility to collect the counters from an AMD Phenom processor. Based on their correlation to the power consumption, four counters, L2-chache-miss, retired-uops, retired-mmx-and-fp-instructions, and dispatch-stalls, are selected for the experiment. Using piece-wise linear model based on least square estimator, they derive a prediction model which maps observed event rates to CPU core power consumption. Their model is evaluated using NAS [51], SPEC-OMP [52], and SPEC 2006 [53] benchmark suites, and shows an average median error of 5.8%, 3.9% and 7.2% respectively. The model performs run-time, power-aware thread scheduling, to suspend and resume processes based on the power consumption.

Joseph and Martonosi [54] present the Castle project which leverages information from hardware to estimate the actual runtime power consumption in different processor units. In some processors, performance counters do not capture events associated with the power consumption. This work analyzes resource utilization of processor's units by defining a list of heuristic approximations such as number of instruction window physical register accesses, Load/Store Queue (LSQ) physical register access, window selection, and number of wakeup logic accesses. An Alpha 21264 microprocessor is resembled using Wattch power simulation, and a combination of performance counters and heuristic approximations for Wattch-Alpha model is used to approximate some utilization factors. Wattch's basic power model is assumed for the experiments and is analyzed with SPEC95 Int and FP benchmarks. The results show that their heuristic approach estimates the utilization rates within 5% error.

Contreras and Martonosi [55] employ performance counters to estimate the power consumption of CPU and memory of an Intel PXA255 processor. Their linear model uses power weights that map processor and memory power consumption. The model is tested with a set of benchmarks including SPEC2000, Java CDC and Java CLDC programming environments, and gives predictions with an average error of 4%. The model can be applied in a number of settings related to the DVFS configuration environment.

Server level power modeling

Server is the main component of the data centers IT infrastructure. It runs most of the computational workloads and store all the data. Due to its heavy use, it consumes large amount of the energy, as shown in Fig. 4, and is the most power proportional equipment available in a data center. This section, presents few studies which analyze and model the energy consumption on server level. In the context of our approach, the following studies leverage the data associated with performance counters, to construct power models which are utilized for predicting and optimizing the energy consumption of the server.

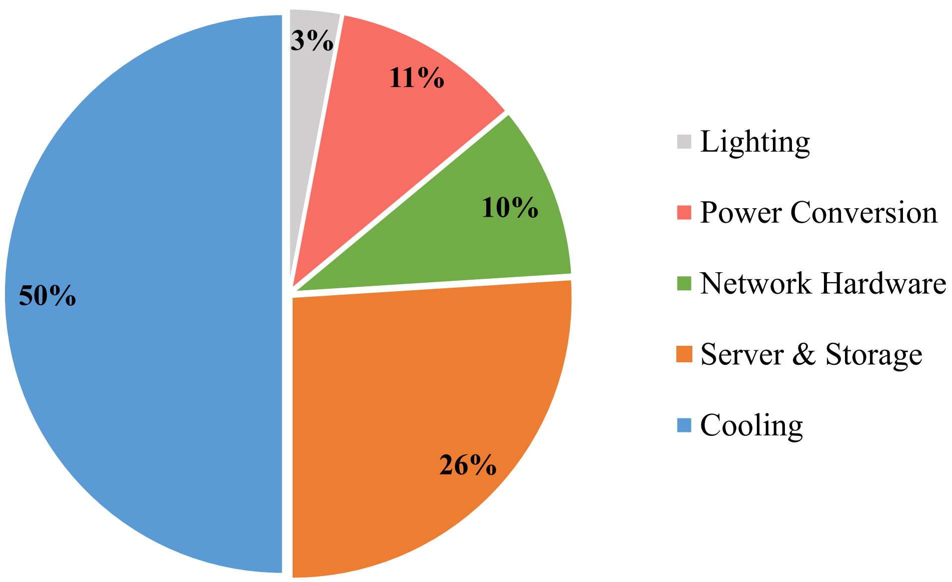

Fig. 4 Distribution of energy consumption in different components of a data center [56].

Bircher and John [57] use Hardware Performance Counters for online measurement of complete system power consumption. They develop power models for microprocessor, access memory, I/O, disk, chipset and Graphics Process Unit (GPU), for two different systems, a quad-socket Intel server and an AMD dual-core with GPU desktop. The two systems are tuned with a set of scientific, commercial and productivity workloads, and selected performance counters events are collected with the Linux *perfctr* [58] device driver. The correlation analysis between the counters and the power consumption is performed using linear and polynomial regression modeling.

Their study shows that events related to the microprocessor have significant correlation to power consumption in the subsystems including memory, I/O, hard drive disk (HDD), chipset and microprocessor, and they can accurately estimate the total system power consumption. Instead of creating a prediction model for the whole server, they use HPCs associated to the processor, to estimate the energy of other subsystems. Moreover, in comparison with our study, they also consider GPU which is not included in our model, because the server we study is not intended for graphical usage neither video or image processing.

Economou *et al*. [59] propose Mantis, a non-intrusive model for real-time server's power estimation. Mantis uses low-overhead OS utilization metrics and performance counters to predict power. It requires a one-time, offline calibration phase to extract basic AC power consumption characteristics and relate them to the system performance metrics. Benchmark is done by individually stressing the major components of the blade system, CPU, access memory, hard disk and network, to derive the basic correlation between their utilization and power consumption. A linear model is used to fit the data relating performance counters to AC power variation. The model is developed for blade and Itanium server and is evaluated using SPECcpu2000 integer and floating-point benchmarks, SPECjbb2000, SPECweb2005, the *streams* benchmark, and matrix manipulation, covering multiple computing domains. The prediction error for Mantis is measured within 10% for most workloads.

While our experiment uses UNIX utilities and custom scripts to stress the components of server in different workloads, Mantis' benchmark runs Generic Application eMUlaTion (GAMUT) [60] to emulate various levels of CPU, memory, network traffic and hard disk. We measure the activity levels of the CPU and RAM using HPCs for fine granularity. Instead, they use Operating System (OS) performance metrics and specifically CPU utilization as variable for measuring the activity of the CPU, while HPCs are used for measuring the impact of RAM.

A.Lewis *et al*. [72] use linear regression to create a power prediction model which dynamically correlates system bus traffic with processor's task activities, RAM metrics, and motherboard power measurements. The accuracy of the model is on average 96%.

The model demonstrates the energy relationship between the workload and the thermodynamics of the server. The regression variables includes the values of the energy consumed by processor, RAM, electromechanical subsystems, motherboard, and HDD. Analysis of variance (ANOVA) [73] is used to calculate the best fit to the data. The validation of the energy model is done using SPEC CPU2006 benchmark suite.

Both Lewis model and our study use HPCs for collecting processor and RAM specific metrics. Nevertheless, there are few major differences. They utilize data that impact the thermodynamics of the server, e.g. ambient temperature, and other electromechanical equipment such as cooling fans and optical drives. However, our study takes into account the incoming and outgoing network packets to consider the impact of network traffic. Their model uses 12 regression variables for prediction with a median error of 4%, whereas we use only 2 variables to estimate power consumption with median error of 5.33%. This is a significant difference when applying mechanisms for real time power estimation.

Data center level power modeling

The power models described in section 2.3 and 2.4 are focused on modeling the energy consumption of processor and server. Beside these individual components, several studies have proposed power models which analyze and estimate the energy consumption in data center level. When constructing higher level power models for data centers, it is essential to understand how the energy is consumed by large groups of servers and what is the role of data center network to the energy consumption.

There are three different types of power models for a group of servers. These are queuing theory based power models, power efficiency metrics based power models, and others. Also, more parameters need consideration compared to power models for a single server. Time delay and sometimes penalties associated with the setup cost i.e. booting the server on, are just few examples. Gandhi *et al.* [61] and Lent [62] propose power consumption models based on queueing theory, which schedule the processes among the servers depending on their power state. There are power models developed based on the data center's performance metrics. Qureshi *et al.* [63] present an energy model for a group of servers, combining the PUE of the whole data center with the linear power model of a single server presented by Fan *et al.* [64].

When modeling energy consumption caused by the data center network, there are multiple components of the network to consider, such as the network equipment and the topology of the network. In higher level abstraction, the energy cost of network links has significant impact to the power consumption. For example, Heller *et al.* [65] present a model for the total network by accumulating the power consumption of an individual link and the cost of an active network switch. Other studies present power models for the network devices. An extensive model by F. Jalali *et al*. [66] describes the total energy consumption of a switch as an addition of input and output energy to and from the switch, the supply and control energies, and the instantaneous throughput.

Summary

Sections 2.3, 2.4, 2.5 presented approaches for power modeling in three different levels. First, we presented power models that predict the consumption of processor; the component of the server that impacts the energy the most. Power models in processor level, were applied during threading scheduling and DVFS to optimize the utilization and reduce the energy consumption. Next, we discussed about system level power models that include other essential components of the server, such as RAM, hard disk, NIC and GPU. Related studies have shown that we can derive power models which predict the energy consumption of the server in real time with reasonable accuracy, less than 10% regardless of the server's workload [59]. Studies that described power models associated with data center's power consumption were presented at the final section. In such cases, modeling is done for optimizing the energy efficiency of groups of servers, or is focused on data center network, where alternative network topologies and efficient routing mechanisms are proposed for efficient network plane.