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Simulating energy-aware networks in large-scale distributed systems

Master's Thesis
Espoo, June 26, 2017

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ABSTRACT OF
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Abbreviations and Acronyms

| | |
|---------------|--|
| 2k/4k/8k mode | COFDM operation modes |
| 3GPP | 3rd Generation Partnership Project |
| ESP | Encapsulating Security Payload; An IPsec security protocol |
| FLUTE | The File Delivery over Unidirectional Transport protocol |
| e.g. | for example (do not list here this kind of common acronyms or abbreviations, but only those that are essential for understanding the content of your thesis. |
| note | Note also, that this list is not compulsory, and should be omitted if you have only few abbreviations |

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Chapter 1

Introduction

1.1 Context of the Study

1.2 Problem statement

Even though there is a growing concern about the energy consumption of large-scale network infrastructures, a search of the literature revealed few studies which address the issue of estimating the energy consumption of these network infrastructures. The existing proposed solutions being packet-level estimators are not scalable (in-terms of memory usage and speed) to be used in the domain of large-scale distributed networks such as cloud, grid, and peer-to-peer computing.

1.3 Aim and Scope

The purpose of this work is first to propose and to implement flow-level energy consumption model in SimGrid and then to show that the implemented model gives reasonably accurate result and it is also scalable for estimating energy consumption of large-scale distributed networks.

In the domain of large-scale distributed network infrastructure, we can categorize energy consuming components into two broad groups: IT equipments (which includes computing servers, storage servers and networking components) and infrastructure components (which includes power provisioning, cooling and lighting components). Since SimGrid already have energy consumption model for computing servers, the scope of this study is on the network component part within the IT equipments category.

1.4 Significance of the Study

1.5 Structure of the Thesis

Chapter 2

Background

In this chapter ...

2.1 Electricity consumption of ICT equipments

ICT equipments consume a significant amount of electricity. A survey conducted by Heddeghem et al. [15] shows the electricity consumption and growth trends of three classes of ICT equipments: personal computers, communication networks, and data centers. Personal computers include equipments such as desktop, laptop and external monitors. Communication networks includes residential network access equipments (such as WiFi routers and modems), network equipments used in offices (such as routers and switches) and telecom-operator network equipments (such as base stations, routers and optical amplification systems). Data-centers house storage and computing servers, communication network equipments, and power provisioning and cooling facilities. In this classification there are overlaps, for instance, telcom operator can have office network equipments and data-centers. After carefully avoiding possible redundant measurements, the researchers estimated absolute electricity consumption and annual consumption growth rate of each category of equipments for the period 2007 and 2012. The results of the study show that the global electricity consumption of ICT equipments in all the three categories combined contributed 3.9% in 2007 and 4.6% in 2012. The estimated annual growth rate of the individual category is 5% for personal computers, 10% for communication networks, and 4% for data-centers. These growth rates are higher than that of the total global electricity consumption, which is 3%.

2.2 Data-center electricity consumption

In Section 2.1 we described data-center's global share in electricity consumption. In this section we describe the components involved within the data center itself.

Electricity consumption units within a typical data-center can be classified into two broad groups [11]: The first group is IT equipments (which includes computing servers, storage servers and networking components) and the other group is infrastructure facilities (which includes power provisioning, cooling and lighting components).

Figure 2.1 [11] shows the electricity consumption proportion of the data-center components. This value differs significantly from one data-center to another [2], for instance, due to architectural difference[14] or energy efficiency of the components. The infrastructure facility components take the large proportion (65%) of the consumption. Though the infrastructure facil-

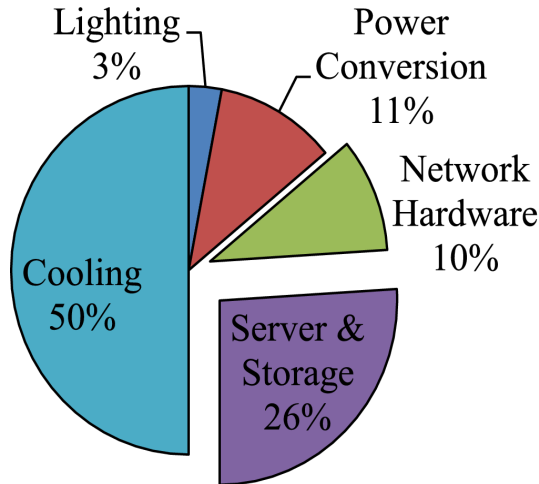


Figure 2.1: Energy consumption percentage of data-center components [11]

ity consumes relatively larger amount of electricity, the focus of this study is on the IT equipment components, particularly on the network equipments.

If we further zoom in on the IT equipments part, we can find server, storage and network equipments. A data-center servers consist of one or more CPU cores, memory and I/O devices. The energy consumption relationship among these components is shown in Figure 2.2. Combined, Memory and CPU units consume the larger amount of energy relative to other components. The fact that CPU is the dominant electricity consuming unit is

exploited by Fan et al. in [12] to model the dynamic power usage of thousands of servers by using only CPU utilization as a parameter. The result of their study was very accurate, with error as low as 1%.

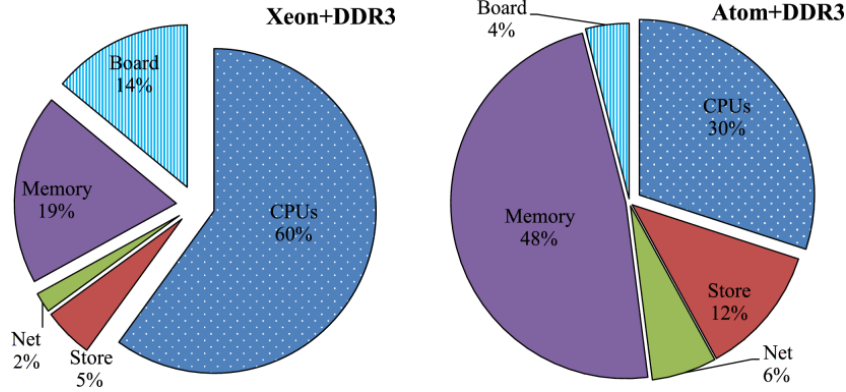


Figure 2.2: Energy consumption percentage of Xeon based (on the left) and Atom based (on the right) servers [11]

2.3 Energy proportionality

The primary reason the study of energy consumption management of network equipment becomes so important is that, in general, ICT equipments do not consume energy proportional to their workload. An ideal ICT equipment is the one which consume zero electricity when it is idle, and it consumes electricity proportional to its workload when it is active. However, the reality is, even power efficient servers consume about 50% of their peak power [3], even when they are doing nothing. This percentage can even reach 85% for network switches [13]. Figure 2.3 in [20] shows the energy proportionality of a typical network equipment. From the graph we can observe that the dynamic power consumption range is narrow. Three approaches are in common use to deal with this situation. The first one is re-engineering network devices so as to make them more energy proportional, device vendors are the prime role player in this aspect. The second approach is related to the operating rate of a network equipment port. A typical switch can operate on different transmission rate (100Mbps, 1 Gbps or 10 Gbps). An active port transmitting at 10 Gbps can consume more energy than if it transmit at 100 Mbps. Rate adaptation is the approach devised to take advantage of this situation. Instead of transmitting at the maximum rate all time, the network port can

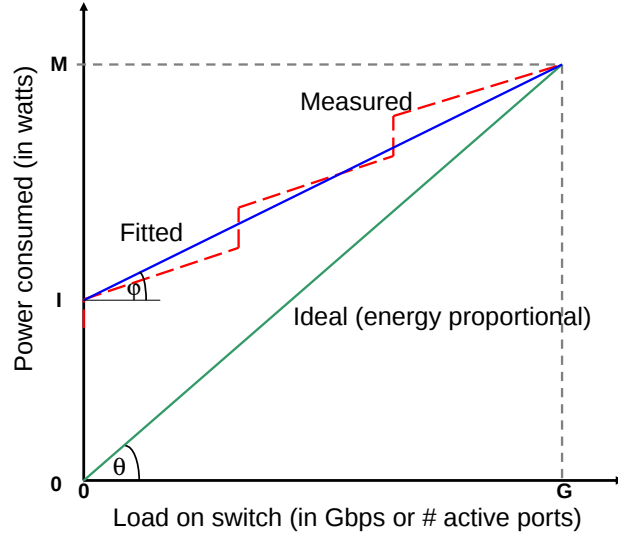


Figure 2.3: Ideal and measured energy proportionality of a network equipment [20]

be made to adapt to the actual traffic load. This energy saving approach is known as Adaptive Link Rate (ALR). The third approach, which is known as Low Power Idle (LPI), allows a network device to send data as fast as possible and then enter low power mode between transfers. The low power mode can further be extended by a technique called packet coalescing, which allows more energy saving [5].

2.4 Packet-level and flow-level Simulators

Packet-level simulators strive to model a given network phenomenon at the granularity level of packets, thus in general they are accepted by the research community to be more accurate compared to flow-level simulators [8]. One of the most popular packet-level simulator is NS-3, which is categorized under discrete-event simulator with events corresponding to sending and receiving of packets [18]. Though packet-level simulators are accepted to be more accurate, they fail to scale well in the field of large-scale distributed networks.

In the area of large-scale networks, flow-level models are the preferred simulation alternative. Rather than modeling a given network phenomenon at a packet level, flow-level models treat a set of packets as a single unit

[8]. The most commonly used definition for flow in the context of computer networking is coined by Claffy et al. in [9]:

“...a flow ...a unidirectional traffic stream with a unique [source-IP-address, source-port, destination-IP-address, destination-port, IP-protocol] tuple ...”

In addition to the five tuple mentioned in the definition, a flow also has a limited time duration. Claffy et al. [9] used a time limit of 64 seconds as a flow duration in their study. Researchers such as Carneiro et al. [7], adopted this same definition to develop flow monitoring module for NS-3, a module that can generate information such as amount of packets or bytes transferred, packets dropped or transmission start and end time for each flow. Barakat et al. in [1] also used the same definition to model traffic at the flow-level for the Internet backbone link. By abstracting away fine details, flow-level models provides easy way to instantiate experiments and they also scale very well for conducting large-scale network simulations [1, 8].

The flow definition given above is not the only one. Any analytical model which capture the characteristics of a given network phenomenon can be considered as flow-level model. In SimGrid, for instance, TCP flow is characterized by bandwidth and end-to-end latency[8].

2.5 Simulating and modeling energy consumption of large-scale networks

One way of conducting energy consumption or any other experiment is to use real production environment or test-bed environment, both are referred to as *in vivo* in [8]. In the former case, handling transient and varying conditions would make the data collection and prediction very difficult and often times, a production environment is also not available for experimentation. In the later case, it requires setting-up a separate testing environment designed solely for the purpose of conducting the desired experiment. This approach apart from being expensive, it requires significant amount of time for experiment setup and, it is also non-repeatable as experimenting with different scenario demands a significantly modified or completely new configuration.

The other alternative for experimenting is simulation, also referred to as *in silico* in [8]. Simulation, unlike real environment, allows great flexibility in terms of experiment configuration, control and repetition. In addition it can also be less time consuming and less expensive. That is why virtually in all computer network related researches simulations are widely used.

In this study we simulate energy-aware large scale distributed networks

using SimGrid (Detail description about SimGrid follows in the next section). When we say large-scale distributed network, we are referring to a set of networks residing inside in the distributed data centers and also the networks that are used to connect them.

The energy consumption E of an equipment depends on the operating power P at time t . The total energy consumption for a time period T is given by Equation 2.1 [21].

$$E(T) = \int_0^T P(t)dt \quad (2.1)$$

Due to the energy proportionality characteristic described in Section 2.3, the common approach used to compute the energy consumption is to divide the power component into two parts: static/idle power (P_{static}) and dynamic power ($P_{dynamic}$) as shown in equation 2.2. Then the total energy is obtained by multiplying the total power, P_{total} by the time duration [11, 17, 20, 21].

$$P_{total} = P_{static} + P_{dynamic} \quad (2.2)$$

For a typical network equipment such as a switch, the static part constitutes the power consumption of the chassis and the line-cards (when all the ports on the line-cards are switched off). The dynamic part, on the other hand, constitutes the power consumption of the switch ports running at a given rate multiplied by the utilization factor [20]. Equation 2.3 shows how to compute the total power for a switch, where P_{switch} , is the total power consumption of a switch, $P_{chassis}$ and $P_{linecard}$ is the idle power consumption of the chassis and the line card, respectively. P_{rate} , is the power consumption of a given port at a given rate and $numports_{rate}$ is the number of ports running at a given rate. The rate can take values such as 10 Mbps, 100 Mbps, 1 Gbps or 10 Gbps.

$$P_{switch} = P_{chassis} + (numlinecards \times P_{linecard}) + \sum_{rate=min}^{max} (numports_{rate} \times P_{rate} \times utilizationFactor) \quad (2.3)$$

2.6 SimGrid

Figure 2.4 shows the structure of SimGrid and how its core works. The top three components are the APIs that users can use to develop their simulation. Both MSG and SMPI are used to specify simulated applications as concurrent processes. The difference is that using MSG, users can simulate any

arbitrary application, whereas, using SMPI users can simulate existing MPI applications, the MPI processes are created automatically from C or Fortran MPI programs. SIMDAG, on the other hand, does not use concurrent processes. It allows users to describe their application as communicating task graph. The next layer, SIMIX, implements the mechanisms that are required to simulate the concurrent process of MSG and SMPI applications. It also provides process control and synchronization functionalities. The bottom layer, SURF, is the simulation core, it simulates the execution of activities on computing or communication resources [8]. In SimGrid for each simu-

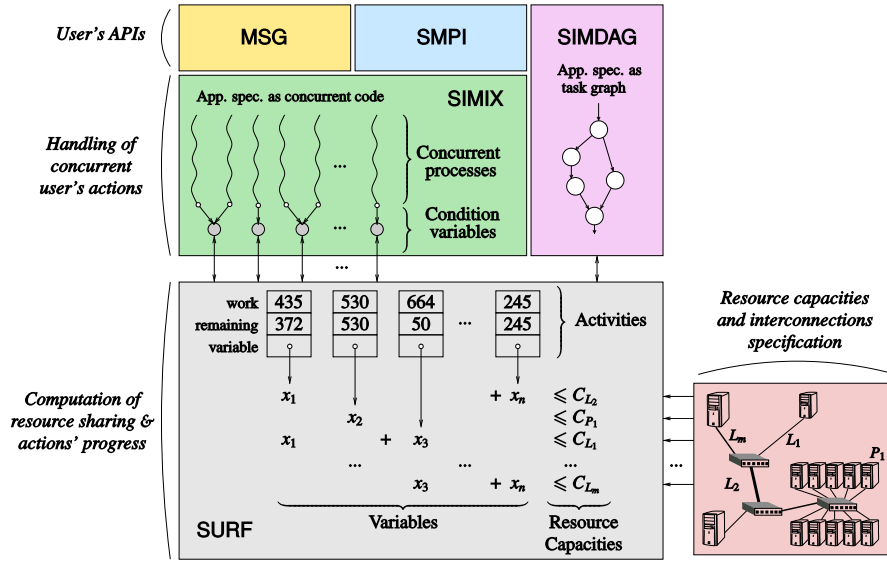


Figure 2.4: Architecture of SimGrid [8]

lated activity, such as computation or data transfer, there is a corresponding condition variable, in Figure 2.4 it is shown in SIMIX box. This condition variable synchronizes the concurrent processes of the simulated applications. The computing (P_x) and the communication (L_x) resources are shown on the bottom-right side of the figure. Computing resources are defined in terms of computing power, whereas, communication resources are defined in terms of bandwidth and latency. As shown in the SURF box, multiple activities can share the same resource (e.g., (x_1, x_n) , (x_1, x_3) or (x_3, x_n)) or one activity can use multiple resources (e.g., x_1 or x_3 or x_n). Activities that share the same resource are limited by the capacity of that resource. Each activity is defined by the total and remaining work to be executed. When the work associated with the activity completes, the corresponding upper layer components receive a notification signal [8].

As we have already pointed out in Section 2.4, the primary advantage of flow-level simulation is its scalability in terms of speed and memory usage. SimGrid uses flow-level analytical model for simulating TCP network phenomenon [8]. To see the scalability of the flow-level model, the SimGrid team compared it with other widely used simulators such as GridSim and OverSim. After simulating 500,000 tasks both on GridSim and SimGrid, the results demonstrate that SimGrid is 257 times faster and 26 times more memory efficient. Similarly, the comparison result with OverSim shows that SimGrid is 15 times faster and it can also simulate scenarios 10 times larger. Concerning the accuracy, though the simulator gives very good accuracy in most case studies, there are situations where it fails to give accurate result. As an example, the comparison study of SimGrid with packet-level simulator GTNetS show that for data size less than 100 KiB there is a significant difference in prediction.

Currently SimGrid is used to simulate different network phenomenon in the area of large-scale distributed systems such as grid, cloud, volunteer and HPC ¹. Concerning energy consumption models, it houses energy models for CPU but there is no model for network equipments. Therefore, the focus of this study is to propose and implement network energy consumption model for SimGrid. The implementation of this model, together with the existing CPU energy model, allows us to estimate the energy consumption of large-scale networks that reside within or outside a data-center that are discussed in Section 2.1 and Section 2.2.

2.7 Related Simulators

In this section we review existing simulators that are proposed for estimating energy consumption of large-scale networks.

2.7.0.1 ECOFEN

Orgerie et al. [21] proposed ECOFEN, an Energy Consumption mOdel For End-to-end Networks. It is a packet-level simulator designed for estimating energy consumption of large-scale networks. Initially the simulator was developed as NS-2 module but currently it is also available as NS-3 module [10]. ECOFEN provides three models for simulating energy consumption at different levels of granularity: *basic*, *linear* and *complete*.

The basic model allows to simulate energy consumption of a network interface card (NIC) at coarse level of granularity. It only accept energy

¹<http://simgrid.gforge.inria.fr/>

consumption value for ON and OFF state of the NIC. The linear model, on the other hand, accepts energy consumption value for the idle state of the NIC and for each bytes processed. This model allows to compute energy consumption of a given network traffic. The complete model like the linear model also considers traffic in its energy computation. The difference is that it offers added flexibility in terms of parameters. Different energy consumption values can be assigned for bytes received or send and also packets received or send. All the three models produce the estimated average energy consumption at milliwatt precision level in the chosen time interval. The interval can be set as small as a millisecond.

ECOFEN module has two main limitations, mainly due to the limitation of the underlying NS-3 simulator. The first limitation comes from the lack of CPU abstraction in NS-3. As we have discussed in Section 2.2, server energy consumption is the second dominant part in typical data center and CPU is the main contributor among server parts such as memory and storage. The energy consumption of CPU is linearly dependent on its operating frequency and its workload. As a consequence of absence of CPU from NS-3, the energy estimation we get from ECOFEN is partial. It only able to simulate energy consumption of network components such as NIC, switches and routers. The second limitation is concerned with the scalability issue. Being a packet-level simulator, the performance of ECOFEN is affected significantly when the number of processed packets grows large. Cornea et al. [10] noticed this scalability problem of ECOFEN during their study of the energy consumption of data transfers in clouds. It took them 5 hours to capture 1 minute of simulated network activity.

2.7.0.2 GreenCloud

Kliazovich et al. [17] proposed GreenCloud, a simulator that can estimate energy consumption of cloud computing data centers. GreenCloud is developed as extension to NS-2 packet-level network simulator. This simulator contains power consumption models both for the computing and communicating components of a typical data center. The power consumption model used for the computing component is shown in Equation 2.4. This equation contains power consumed by the fixed parts (such as bus, memory and disk) which consume power independent of the operating frequency f of the computing component CPU and the power consumed by the CPU (P_f) operating at a given frequency f . This model allows for lowering the operating frequency of the CPU when workload becomes below some predefined threshold in order to decrease the power consumption.

$$P_{computing} = P_{fixed} + P_f \times f^3 \quad (2.4)$$

h= The power consumption model used in GreenCloud for the communicating components is the one shown in Equation 2.3. The equation shows the static power consuming parts (such as the chassis($P_{chassis}$) and the active line cards($P_{linecard}$) and the dynamic part (P_{rate}) is the energy consumed by the port running at a particular line rate for a given traffic load.

This simulator is limited in three aspects: (1) in the number of allowed CPU cores, (2) in versatility, and (3) in scalability. The first limitation is that only one CPU core is allowed per simulated node. This hinders the study of energy consumption of multi-core computing nodes. The second one is that we can not use this simulator outside the cloud computing domain such as grid, volunteer, peer-to-peer or HPC, at least that is not the authors original intention when they develop this simulator. The available features of the simulators are tuned towards cloud computing applications only. This limits its versatility. The third limitation deals with the scalability issue. The fine grain details provided by GreenCloud and the packet-level processing approach of the underlying NS-2 simulator is advantageous for getting accurate result when simulating relatively small networks. However, for large-scale distributed networks, it is not scalable. In related to this, the authors have mentioned that their solution gets slower and slower as the number of simulated nodes increases beyond few thousands and also as the number of packets processed increases. In addition to this speed problem, we also expect the memory footprint to increase as the processed packets and the number of simulated nodes increases, even though the authors did not say anything about it.

Chapter 3

Environment

In this study we employ SimGrid and the ECOFEN module of NS-3 simulator.

Chapter 4

Methods

One approach for estimating energy consumption of a given network is by employing actual power meter to measure the power drawn by involved network and computing components. A good example for such case is the measurement that Fan and his team conducted[12]. In this study the authors have managed to monitor power consumption of several thousand of servers over a period of six months on real live workload. Mahadevan et al. have also done a similar power measurement on a production environment for studying power consumption behavior of networking devices such as switches and routers. If the measurements are done correctly, this approach produces the most real picture of the network under investigation compared to the other approaches discussed in subsequent paragraphs. However, this approach has certain inherent drawbacks. First real production networks might not be available for experimentation. Even if they become available, the transient and varying nature of the production environment makes it hard to repeat the experiment. Second we have little or no control over factors affecting the measured power consumption. We do not have the privileged of injecting or modifying the traffic or the workload in order to test different experimental hypothesis. To have a full control we need another approach. That is what we discuss next.

Experimental testbed is another approach that researchers have used to study power consumption characteristics of different computing and networking equipments. In this approach first a separate network is setup and configured solely for the purpose of conducting experiments. Then researchers make measurements by manipulating factors that affect power consumption according to the hypothesis that they want to test. Unlike the previous one, this approach offers greater flexibility over the experimental parameters. In the power measurement study scenario that we are discussing, the researcher can change parameters such as traffic rate, packet size, inter-packet time

interval and transmission protocol used (TCP/UDP). Sivaraman et al. in [23] have setup experimental testbed for determining per-packet processing and per-byte receipt, storage, queuing, and transmission power consumption. The experiment setup involved hardware-based traffic generator (which gives fine grain control over parameters such as the packet size, inter-packet interval and data rate), NetFPGA¹ experimental router and digital oscilloscope for measuring the power draw of the NetFPGA router. A similar experiment but with a commercial switches of different vendors is explained in [22]. The primary advantages of this approach is that the researcher can have full control over the experimental parameters provided by the tools involved in the testbed and experimental result can also be very accurate. The first disadvantage though is that it can easily become very expensive when we want to experiment on large-scale level. The second disadvantage is that experimenting on different scenario might require considerable reconfiguration and even a completely new testbed, which apart from limiting the flexibility, it can also be very costly, time and effort consuming. We need an approach which overcome these shortcomings. That is, we need an approach which gives full control over the experiment, which is reasonably accurate, less expensive and very flexible.

Simulation is the most widely used approach in computer network researches [26]. It has several advantage compared to the other two approaches mentioned before. First it is relatively easy to study, for instance, the performance of non-existing network protocol or algorithm using simulator. To give an example one can propose and validate, by simulation experiment, a new energy-aware routing protocol or algorithm for wired or wireless networks. This is exactly what Swain et al. [24] did in their new energy-aware routing protocol proposal for wireless sensor networks. Second, though it depend on the design of the particular simulator used, in general, simulation approach allows running large scale experiments that involve hundreds and thousands of nodes compared to the other two approaches. In [21] and [10], ECOFEN - the NS-3 module is used to simulate energy consumption of large-scale networks with nodes more than 600 and 1000, respectively. In [17], the authors studied energy consumption of data center networks with two-tier and three-tier architectures that encompasses 1536 nodes. Third, in simulation scaling does not incur monetary cost, rather, it is limited by performance factors such as runtime and memory usage [26]. Fourth, the researcher has great flexibility and full control over the simulation experiment.

Though simulation experiment has quite a lot of advantages over experiments done on production environment or experimental testbeds, it faces

¹<http://www.netfpga.org/>

one big challenge, accuracy. In the process of approximating the real network phenomenon in the simulation model, some less significant concepts are abstracted away, for instance, to reduce complexity or to gain performance improvement, which results in unavoidable loss of accuracy. However, in other instances the models used in a given simulator might fail to correctly capture the simulated real network phenomenon. In [25] the authors demonstrated incorrect modelings found in popular simulators such as OptorSim, GridSim and CloudSim. Therefore, (in)validating the correctness of a simulator is important task that should be undertaken before any simulation experiment for two related reasons. Either to know the boundaries within which the simulator used produce reasonably accurate results, or to know if the simulator produce the expected or the correct result. The validation can be done either by comparing the output of the simulator against accurate measurements obtained from real networks or by comparing the output against another simulator whose accuracy is already known[16].

4.1 Our Approach

The purpose of this study is to implement analytical or flow-level (as opposed to packet-level) energy consumption model for SimGrid and to show that the implemented model produce reasonably accurate result and is also scalable for estimating energy consumption of large-scale distributed networks. To achieve this goal, we use the simulation approach among the three alternatives discussed above.

Before describing the details of our approach, let us first justify why we end up with the relatively complex method shown in Figure 4.1. There is experimental test-bed (Grid5000²) in France that we have access to. Grid5000 is experimental test-bed specifically designed for studying large-scale distributed networks [6]. However, we could not use it for our purpose (i.e., for studying large-scale flow-level relationship of power consumption and traffic) as the nodes are not equipped with tools such as traffic generator and power meter. As a result, we opted to use a packet-level simulator with power consumption models obtained from literature. Subsequent paragraphs describe the specific steps we followed in our approach.

As we have discussed in Chapter 2, SimGrid already have energy consumption model for CPU which corresponds to the computing part of a given large-scale network. What we wanted to add is energy consumption model for communication components such as switches and routers. Therefore, the

²<https://www.grid5000.fr/mediawiki/index.php/Grid5000:Home>

initial task in our approach is to study literatures ((1) in Figure 4.1) in order to find a model which describe the power consumption characteristics of communication equipments such as switches and routers. Our search returned the linear relationship that we have described in Equation 2.2 [4, 19, 20, 23]. This equation tells us that the power consumption of a network equipment constitutes the idle and dynamic components. The idle power consumption represents the power drawn by the equipment while it is on but with no traffic. The dynamic consumption, on the other hand, represent the additional power drawn due to network traffic. The next task ((3) in Figure 4.1) is to implement this linear model for SimGrid and (in)validate its accuracy against ECOFEN module ((4) in Figure 4.1)[10, 21]. The final task ((7) in Figure 4.1) is to show the scalability of the implemented flow-level model against the existing packet-level model in ECOFEN. For this we design and run two kinds of experiments ((5) and (6) in Figure 4.1), one for speed and one for memory usage.

We chose to use ECOFEN as packet-level simulator to compare the accuracy and performance of the implemented model for two primary limitations apparent in the other alternative simulator, GreenCloud [17]. The first limitation is that GreenCloud is designed for cloud computing environment. This is in contrary to one of SimGrid’s main designed principle, versatility [8]. ECOFEN, on the other hand, is not tied to one particular large-scale networking paradigm, therefore, suits more for our purpose. The second limitation of GreenCloud is that it is build on top of currently obsolete NS-2 simulator. In comparison, though ECOFEN was also initially built as NS-2 simulator module, currently it is rewritten for NS-3 [10]. One of the major advantage of using NS-3 over NS-2 is that NS-3 performs considerably well in both runtime and memory-usage metrics [26].

In the accuracy-validation and scalability-comparison experiments mentioned in our approach, we are comparing the newly implemented flow-level model in SimGrid simulator against another packet-level simulator model implemented in ECOFEN module. This simulator-to-simulator comparison is valid only if the later simulator model, against which the new implementation is to be validated, is known to be accurate. However, we could not find any information that tell us the accuracy of the ECOFEN module. Therefore, we designed a validation experiment ((2) in Figure 4.1) for ECOFEN as described in the next section.

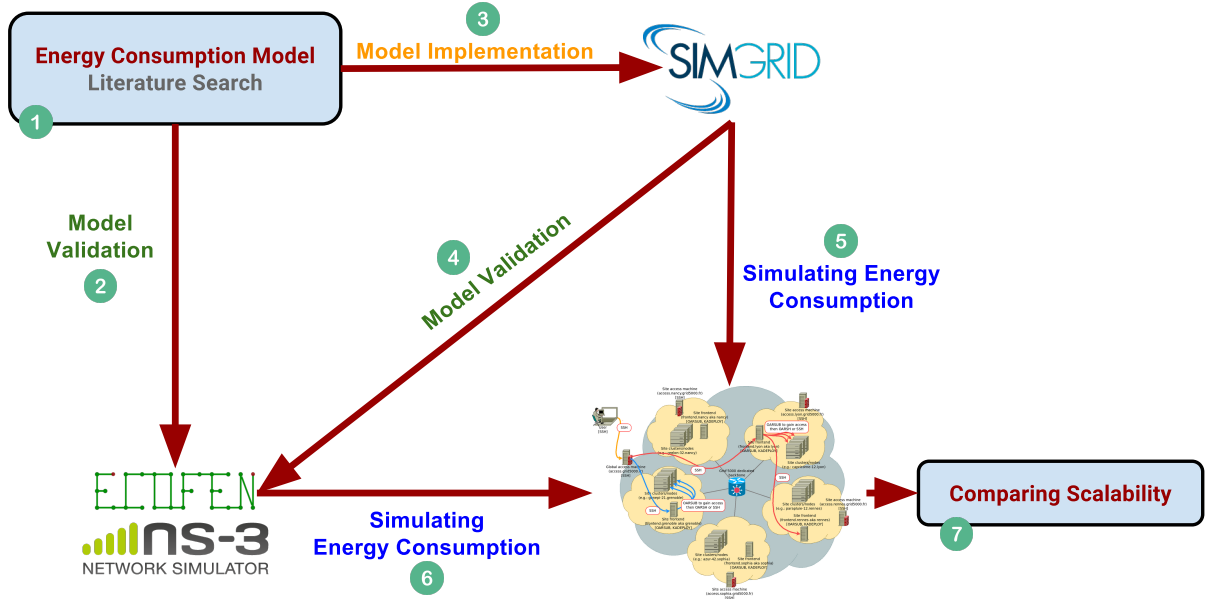


Figure 4.1: Summary of the method we followed in this study

4.2 Validating ECOFEN

ECOFEN has three models with names *basic*, *linear* and *complete* that we have discussed in Section 2.7 of Chapter 2. The *linear* and *complete* models

Chapter 5

Implementation

Here I describe about SimGrid implementation of energy consumption models.

The challenges encountered

How we tackled the challenges

The limitation of the implementation

Chapter 6

Evaluation

After conducting experiments both on SimGrid and other Simulators, here we compare the result

Chapter 7

Discussion

At this point, you will have some insightful thoughts on your implementation and you may have ideas on what could be done in the future. This chapter is a good place to discuss your thesis as a whole and to show your professor that you have really understood some non-trivial aspects of the methods you used...

Chapter 8

Conclusions

Time to wrap it up! Write down the most important findings from your work. Like the introduction, this chapter is not very long. Two to four pages might be a good limit.

Bibliography

- [1] BARAKAT, C., THIRAN, P., IANNACCONE, G., DIOT, C., AND OWEZARSKI, P. Modeling Internet backbone traffic at the flow level. *IEEE Trans. Signal Processing* 51, 8 (2003), 2111–2124.
- [2] BARROSO, L. A., CLIDARAS, J., AND HÖLZLE, U. *The Datacenter as a Computer: An Introduction to the Design of Warehouse-Scale Machines, Second Edition*. Synthesis Lectures on Computer Architecture. Morgan & Claypool Publishers, 2013.
- [3] BARROSO, L. A., AND HÖLZLE, U. The case for energy-proportional computing. *IEEE Computer* 40, 12 (2007), 33–37.
- [4] BEISTER, F., DRÄXLER, M., AELKEN, J., AND KARL, H. Power model design for ICT systems - A generic approach. *Computer Communications* 50 (2014), 77–85.
- [5] BOLLA, R., BRUSCHI, R., DAVOLI, F., AND CUCCHIETTI, F. Energy efficiency in the future internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures. *IEEE Communications Surveys and Tutorials* 13, 2 (2011), 223–244.
- [6] BOLZE, R., CAPPELLO, F., CARON, E., DAYDÉ, M. J., DESPREZ, F., JEANNOT, E., JÉGOU, Y., LANTERI, S., LEDUC, J., MELAB, N., MORNET, G., NAMYST, R., PRIMET, P., QUÉTIER, B., RICHARD, O., TALBI, E., AND TOUCHE, I. Grid’5000: A large scale and highly reconfigurable experimental grid testbed. *IJHPCA* 20, 4 (2006), 481–494.
- [7] CARNEIRO, G., FORTUNA, P., AND RICARDO, M. Flowmonitor: A network monitoring framework for the network simulator 3 (NS-3). In *4th International Conference on Performance Evaluation Methodologies and Tools, VALUETOOLS ’09, Pisa, Italy, October 20-22, 2009* (2009), p. 1.

- [8] CASANOVA, H., GIERSCHE, A., LEGRAND, A., QUINSON, M., AND SUTER, F. Versatile, scalable, and accurate simulation of distributed applications and platforms. *J. Parallel Distrib. Comput.* 74, 10 (2014), 2899–2917.
- [9] CLAFFY, K., MILLER, G., AND THOMPSON, K. The nature of the beast: Recent traffic measurements from an Internet backbone. In *Proceedings of INET* (1998), vol. 98, pp. 21–24.
- [10] CORNEA, B. F., ORGERIE, A., AND LEFÈVRE, L. Studying the energy consumption of data transfers in clouds: the ecofen approach. In *3rd IEEE International Conference on Cloud Networking, CloudNet 2014, Luxembourg, Luxembourg, October 8-10, 2014* (2014), pp. 143–148.
- [11] DAYARATHNA, M., WEN, Y., AND FAN, R. Data center energy consumption modeling: A survey. *IEEE Communications Surveys and Tutorials* 18, 1 (2016), 732–794.
- [12] FAN, X., WEBER, W., AND BARROSO, L. A. Power provisioning for a warehouse-sized computer. In *34th International Symposium on Computer Architecture (ISCA 2007), June 9-13, 2007, San Diego, California, USA* (2007), pp. 13–23.
- [13] FIANDRINO, C., KLIASOVICH, D., BOUVRY, P., AND ZOMAYA, A. Y. Performance metrics for data center communication systems. In *8th IEEE International Conference on Cloud Computing, CLOUD 2015, New York City, NY, USA, June 27 - July 2, 2015* (2015), pp. 98–105.
- [14] GYARMATI, L., AND TRINH, T. A. How can architecture help to reduce energy consumption in data center networking? In *Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking, e-Energy 2010, Passau, Germany, April 13-15, 2010* (2010), pp. 183–186.
- [15] HEDDEGHEM, W. V., LAMBERT, S., LANNOO, B., COLLE, D., PICKAVET, M., AND DEMEESTER, P. Trends in worldwide ICT electricity consumption from 2007 to 2012. *Computer Communications* 50 (2014), 64–76.
- [16] JAIN, R. *The art of computer systems performance analysis - techniques for experimental design, measurement, simulation, and modeling*. Wiley professional computing. Wiley, 1991.

- [17] KLIAZOVICH, D., BOUVRY, P., AND KHAN, S. U. Greencloud: A packet-level simulator of energy-aware cloud computing data centers. *The Journal of Supercomputing* 62, 3 (2012), 1263–1283.
- [18] LLC, M. NS-3 simulator, 2017.
- [19] MAHADEVAN, P., BANERJEE, S., AND SHARMA, P. Energy proportionality of an enterprise network. In *Proceedings of the 1st ACM SIGCOMM Workshop on Green Networking 2010, New Delhi, India, August 30, 2010* (2010), pp. 53–60.
- [20] MAHADEVAN, P., SHARMA, P., BANERJEE, S., AND RANGANATHAN, P. A power benchmarking framework for network devices. In *NET-WORKING 2009, 8th International IFIP-TC 6 Networking Conference, Aachen, Germany, May 11-15, 2009. Proceedings* (2009), pp. 795–808.
- [21] ORGERIE, A., LEFÈVRE, L., LASSOUS, I. G., AND LÓPEZ-PACHECO, D. M. ECOFEN: An end-to-end energy cost model and simulator for evaluating power consumption in large-scale networks. In *12th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, WOWMOM 2011, Lucca, Italy, 20-24 June, 2011* (2011), pp. 1–6.
- [22] SIVARAMAN, V., REVIRIEGO, P., ZHAO, Z., SÁNCHEZ-MACIÁN, A., VISHWANATH, A., MAESTRO, J. A., AND RUSSELL, C. An experimental power profile of energy efficient ethernet switches. *Computer Communications* 50 (2014), 110–118.
- [23] SIVARAMAN, V., VISHWANATH, A., ZHAO, Z., AND RUSSELL, C. Profiling per-packet and per-byte energy consumption in the netfpga gigabit router. In *2011 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)* (April 2011), pp. 331–336.
- [24] SWAIN, A. R., HANSDAH, R. C., AND CHOUHAN, V. K. An energy aware routing protocol with sleep scheduling for wireless sensor networks. In *24th IEEE International Conference on Advanced Information Networking and Applications, AINA 2010, Perth, Australia, 20-13 April 2010* (2010), pp. 933–940.
- [25] VELHO, P., SCHNORR, L. M., CASANOVA, H., AND LEGRAND, A. On the validity of flow-level tcp network models for grid and cloud simulations. *ACM Trans. Model. Comput. Simul.* 23, 4 (2013), 23:1–23:26.

- [26] WEINGÄRTNER, E., VOM LEHN, H., AND WEHRLE, K. A performance comparison of recent network simulators. In *Proceedings of IEEE International Conference on Communications, ICC 2009, Dresden, Germany, 14-18 June 2009* (2009), pp. 1–5.

Appendix A

First appendix

This is the first appendix. You could put some test images or verbose data in an appendix, if there is too much data to fit in the actual text nicely.

For now, the Aalto logo variants are shown in Figure A.1.



(a) In English



(b) Suomeksi



(c) På svenska

Figure A.1: Aalto logo variants