



**NTNU – Trondheim**  
Norwegian University of  
Science and Technology

# Measuring and Optimizing Energy Efficiency in Internet Communication

Implementing a Packet-Level Energy Model  
for Content Delivery Networks

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Master in Security and Mobile Computing

Submission date: June 2013

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**Student:** Gitanjali Sachdeva

**Problem description:**

With the increase in demand of internet usage, internet service providers (ISPs) are focusing on providing faster and cheaper access to their users by deploying extra infrastructure. As a result, there is an increase in the overall network power consumption contributing to higher carbon emissions in the ICT sector. Therefore, network devices and infrastructure, which make up a considerable share of ICT power consumption, should be made more energy-efficient.

Green ICT (Information and Communication Technology) aims at reducing the environmental impacts of ICT operations, maximizing energy efficiency and promoting recyclability. Networks play a crucial role in the overall green ICT initiatives. Various research efforts are being made by network equipment manufacturers as well as researchers to promote energy efficiency in the networks.

The target of this master thesis is to develop mechanisms that allow measuring the energy consumption in networks and using such mechanisms to optimize network usage.

**Responsible professor:** Professor Yuming Jiang, NTNU, Norway

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## Abstract

Green ICT (Information and Communication Technology) aims at reducing the environmental impacts of ICT operations, maximizing energy efficiency and promoting recyclability. The ICT industry is resource intensive with rapidly increasing demands for more infrastructure and power. It is heavily dependent on full-time network connectivity. Therefore, networks play a crucial role in the overall green ICT initiatives. Various research efforts are being made by network equipment manufacturers as well as researchers to promote energy efficiency in the networks.

The target of this master thesis is to develop mechanisms that allow measuring the energy consumption in networks and using them to optimize network usage. The thesis implements a packet-level energy accounting model using NS-3 simulator. The main idea is that IP packets collect the information of energy they consume at each hop while traversing a network. This information is later processed to account for the overall network energy consumption.

The thesis work analyzes a specific use case of selecting energy-efficient servers in Content Delivery Networks (CDNs) to deliver content to end users. The energy model is implemented and tested for different traffic scenarios and sample network topologies. Simulation results show that the model can prove highly useful in the CDN use case. The energy accounting scheme allows end users to choose energy-efficient server alternatives for accessing content over the internet. End users are made aware of their carbon footprint and are able to contribute to green networking.

Additionally, there is also a possibility to integrate the model with other network performance metrics such as network throughput in order to increase its usability.





## Preface

This thesis is written as a part of the Erasmus Mundus NordSecMob (Nordic Security and Mobile Computing) Master's Program. I am glad to have taken up the challenging project. The thesis work has been a great learning experience.

I would like to thank my thesis supervisor, Professor Jukka K. Nurminen, and instructor, Dr. Matti Siekkinen, for their invaluable guidance throughout the thesis work. I am also thankful to Professor Yuming Jiang for supervising the thesis remotely. I express my gratitude to Mr. Mark Sevalnov who previously worked on the topic. His work provided a useful background for understanding the problem statement and the core concepts. Finally, I am very grateful to my friends and family for their support and encouragement.

Espoo, Finland, June 30, 2013  
Gitanjali Sachdeva



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# Chapter 1

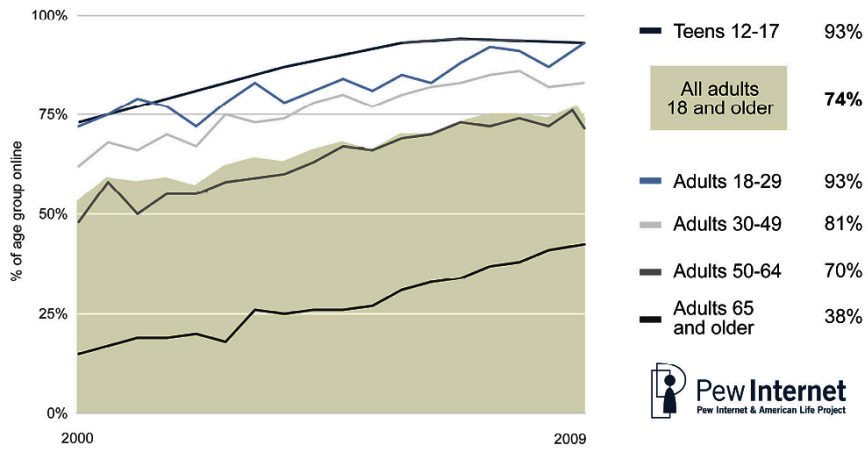
## Introduction

Twenty-first century has seen a huge boost in the field of Information and Communication Technology (ICT) with the recent advancements in mobile technology. A variety of innovative devices such as tablets and smartphones have recently taken over the mobile market which was previously dominated by laptops. These devices support a multitude of applications and services that connect the users over internet. Some of the most popular services are online social networks such as Facebook and Twitter where information is increasingly being exchanged via internet communication [LPSZ10]. Without access to internet, usefulness of such devices reduces greatly. Figure 1.1 shows a growth in the number of internet users between year 2000-2009 where more than half of the users access internet wirelessly.

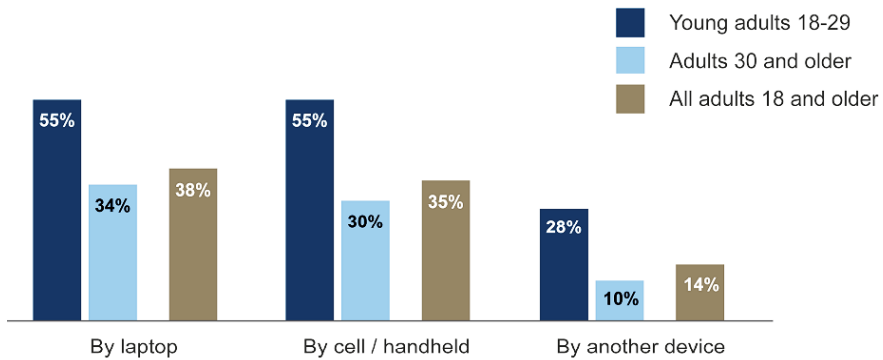
Another factor contributing to increased internet usage is the emergence of data centers and cloud services. Data centers manage vast amounts of data which is made available to end users via network access. Data and computing capabilities are also being transferred to the cloud [FGJ<sup>+</sup>09]. This facilitates data availability to end users across multiple devices and platforms. Moreover, many end user devices are battery-constrained. In order to get a longer battery life, computations are being offloaded to cloud [KL10, CIM<sup>+</sup>11]. Therefore, technology is increasingly relying on internet access.

### 1.1 Problem Description

With the increase in demand of internet usage, internet service providers (ISPs) are focusing on providing faster and cheaper access to their users by deploying extra infrastructure [BBDC11]. As a result, there is an increase in the overall network power consumption contributing to higher carbon emissions in the ICT sector [Web08]. Figure 1.2 shows that the carbon footprint due to ICT sector is expected to grow three times by the year 2020 than it was in the year 2002. Therefore, network devices and infrastructure, which make up a considerable share of ICT power consumption,



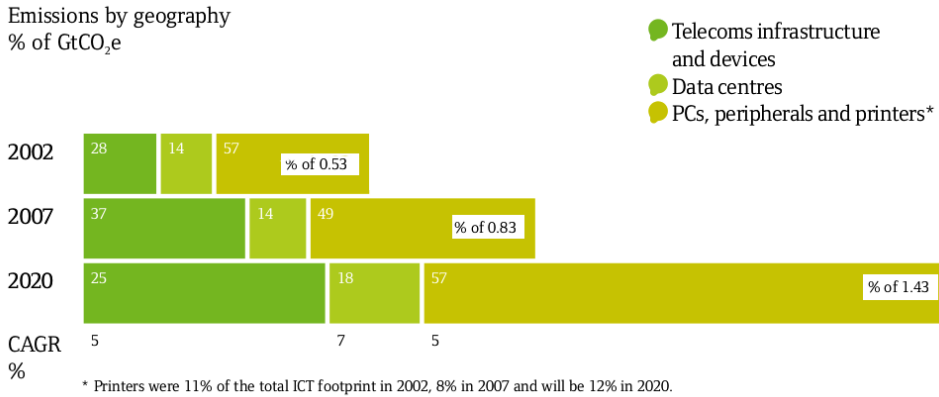
(a) Changes in Internet Usage



(b) Accessing Internet Wirelessly

**Figure 1.1:** Changing Trends in Internet Access [LPSZ10].

should be made more energy-efficient.



**Figure 1.2:** The Global ICT Carbon Footprint [Web08].

Various research efforts are being made by network equipment manufacturers as well as researchers to promote energy efficiency in internet communication. The target of this master thesis is to develop mechanisms that allow measuring the energy consumption in networks and using such mechanisms to optimize network usage.

## 1.2 Objectives

This master thesis implements an energy accounting model based on the concept of packet-level energy accounting proposed in earlier work [SNYJ12]. The main objectives of this thesis work are as follows:

- Assessing the usability of packet-level energy accounting mechanism to promote energy efficiency in internet communication [SNYJ12].
- Analysing the use case of selecting energy-efficient servers in Content Delivery Networks (CDNs). The energy model is implemented and tested for different traffic scenarios and network topologies using NS-3 simulator<sup>1</sup>.
- Interpretation of results and reforming the model accordingly for better energy saving outcomes.
- Integration of the model with other network performance metrics such as network throughput in order to increase its usability.

<sup>1</sup><http://www.nsnam.org/>

- Analysing practical challenges and limitations of the model.

### 1.3 Contribution

The thesis work successfully conceptualizes and implements a packet-level energy accounting model whose idea was initially proposed by Siekkinen et al. [SNYJ12]. The idea of using packet probes for estimating various network characteristics and complexities is not new for researchers. For example, it has been used to detect packet losses in networks [BMVB11] or to understand complex routing mechanisms. However, the idea to use packet-probing for energy accounting in CDNs is quite novel.

Through this thesis work, we show that the packet-level energy accounting mechanism can be used for promoting energy efficiency in networks. The thesis work analyzes the use case of selecting energy-efficient servers in CDNs using simple network topologies and traffic scenarios. Using the energy model, it is possible to predict power variations in CDNs which may occur as a result of content delivery between any given client-server pair.

In the thesis, we also discuss about integrating the energy model with existing network performance metrics. The energy accounting model implemented in this thesis is capable of promoting energy efficiency in networks without compromising network performance and QoS.

### 1.4 Structure

The remainder of this report is organized as follows:

**Chapter 2: Green ICT** reviews the academic literature on green computing and initiatives taken to promote it in the ICT sector. Later, this chapter introduces the area of green networking and discusses different approaches to promote energy efficiency in networks.

**Chapter 3: Packet-level Energy Accounting** provides a conceptual overview of the packet-level energy accounting mechanism. It explains various use cases where the concept can be implemented to promote green networking.

**Chapter 4: Energy Accounting Model** discusses various challenges and goals in designing a packet-level energy accounting model. This chapter provides a technical background of the model and describes the approach used to calculate per packet energy consumption in networks. Later, this chapter explains the implementation of this model in NS-3 simulator for the use case of selecting energy-efficient servers in

CDNs.

**Chapter 5: Simulation Results and Analysis** presents an energy-accounting protocol for analyzing the use case of CDNs. The observations and analysis for different simulation scenarios are also presented in this chapter.

**Chapter 6: Discussion** reviews the energy model and discusses about integrating the model with other network performance metrics.

**Chapter 7: Conclusion and Future Work** concludes the thesis work by summarizing the achieved results. It also suggests possible future work.

## 1.5 Conventions

This report contains some definitions and quotes from other sources. The conventions used are described below.

Direct quotation from a source is written in italics and with quotation marks. As an example: “*Energy efficiency ...*” [some reference]

Newly formulated definitions or statements are written in italics. As an example: *Energy efficiency...*



# Chapter 2

## Overview of Green ICT

This chapter provides an overview of green computing and its importance in today's ICT industry. Later, it introduces the area of green networking and discusses different approaches to promote energy efficiency in networks.

### 2.1 Green ICT

Green Computing or Green ICT refers to the form of computing or ICT that aims at reducing the environmental impacts of ICT operations, maximize energy efficiency and promote recyclability [HA09]. San Murugesan defines green computing as *“the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems - such as monitors, printers, storage devices, and networking and communications systems - efficiently and effectively with minimal or no impact on the environment.”* [Mur08].

ICT industry is a resource intensive industry where the demands for more infrastructure and power are growing at a rapid rate. It places a heavy burden on power grids and also contributes to greenhouse gas emissions [FZ08]. Energy consumption of ICT can be broadly divided among different categories of equipment [LVHV<sup>+</sup>12a]. First category is *data centers* including computing, storage, network, cooling, power supply equipment. Second category is that of *PCs* including laptops and desktops. Third category includes *network* infrastructure comprising of devices such as routers, switches, modems, gateways and last category comprises *other devices* such as mobile phones, printers, fax machines. Lambert et al. [LVHV<sup>+</sup>12b] has presented statistics on the worldwide electricity consumption in these categories, as shown in Table 2.1.

Green computing has been taken up by several governments and industries worldwide. Governments are heavily investing in reforms and measures needed to mitigate environmental impacts of technology [ZL12, BH12, Och12].

<b>Category</b>	<b>Power cons. 2008 (GW)</b>	<b>Growth rate (p.a.)</b>	<b>2020 prediction (GW)</b>
Data centers	29	12%	113
PCs	30	7.5%	71
Network Equip- ment	25	12%	97
TVs	44	5%	79
Other	40	5%	72
<b>Total</b>	<b>168</b>		<b>433</b>
Worldwide Elec- tricity	2350	2.0%	2970
ICT fraction	7.15%		14.57%

**Table 2.1:** Worldwide ICT Power Consumption [LVHV<sup>+</sup>12b].

<b>Country</b>	<b>Green Measures as % of Total Stimulus</b>	<b>Amount Spent on Green Mea- sures (billions)</b>	<b>Amount Spent on Fiscal Stim- ulus (billions)</b>
South Korea	79%	\$59.9	\$76.1
EU	64%	\$24.7	\$38.80
China	34%	\$218	\$649.1
Australia	21%	\$9.30	\$43.8
France	18%	\$2.50	\$26.70
Germany	13%	\$13.8	\$104.8
US	12%	\$117.2	\$976.9
UK	11%	\$3.7	\$34
Canada	9%	\$2.8	\$31.8
Japan	6%	\$36	\$639.9

**Table 2.2:** Green Measures as Percentage of Total Stimulus [BAWL09].



*Energy Star*<sup>1</sup> program was one of the very early initiatives by the U.S. government towards green computing. Later, several other countries joined the initiative to promote energy-efficient products and practices. Table 2.2 shows statistics regarding the investment made by several governments to promote green ICT and these numbers have increased since then. Green initiatives may involve one of the following [Ser12].

- Greening of hardware and software solutions.
- Using ICT to reduce energy consumption in other sectors.
- Green ICT as an innovative model to spread awareness and bring changes in lifestyle of people.

IT industry can take such initiatives in several areas to promote green computing [Min07]. Some of the major areas can be categorized as follows.

### *Client Side*

Client devices such as PCs, printers, mobile phones, tablets can contribute to vast amounts of energy savings. Moreover, some of these devices are battery constrained. They should be energy-efficient to provide better user experience [FDK11]. These devices are normally equipped with power saver modes or sleep modes in order to make them energy-efficient [PLL10]. Apart from that, the devices also need to be energy proportional [Cam10, BH07]. It means that the amount of energy used by such devices should be proportional to the amount of functions performed in a given time duration.

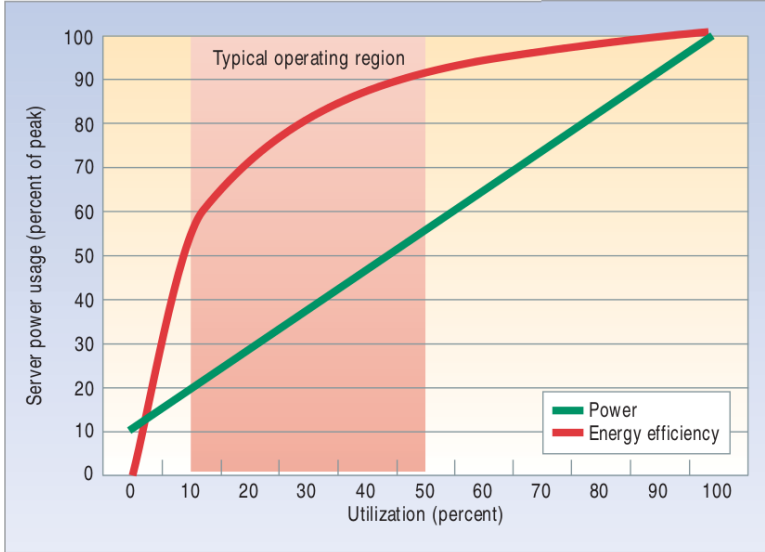
### *Data Centers*

Data centers are emerging as key players in ICT with the increase in amounts of data and content being stored over the internet. Data centers spend huge amounts of power in running servers and storage equipment as well as providing cooling facilities for the infrastructure [LVHV<sup>+</sup>12a]. Aggregate power usage of data centers doubled worldwide during the period 2000 - 2005 [Koo08]. Power consumption of computing and storage infrastructure can be minimized by energy-efficient workload distribution and scheduling schemes [LP07, GT11, TTH<sup>+</sup>13]. Energy efficiency of data centers can be improved by using energy-efficient equipment, reducing cooling requirements, adopting environment friendly designs and taking measures to curb energy consumption in data centers [Mur08]. Some schemes aimed at reducing cooling requirements may involve building data centers in cold geographic locations

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<sup>1</sup><http://www.energystar.gov/>

and using natural cooling [VVHC<sup>+</sup>10]. Also, heat generated can be recycled to heat up buildings in such locations. Such methods are being widely adopted to reduce the electricity bills and carbon footprints of data centers. Barroso et al. [BH07] has described the concept of energy proportionality for servers in data centers. The authors call for energy proportional systems which consume very less power when idle and gradually consume more power as their utilization increases.



**Figure 2.1:** Power Usage and Energy Efficiency in an Energy-proportional Server [BH07].

### *Networks*

Networks comprise a considerable share of total ICT power consumption as depicted in Table 2.1. ICT sector is heavily dependent on full-time network connectivity [BCRR12]. Networks play a major role in the overall green computing initiatives. Gupta et al. [GS03] is one of the initial research works that has stressed on the importance of saving energy in networks. A detailed discussion on green networking is presented later in this chapter.

### *Software and Applications*

Apart from creating energy-efficient hardware, it is also important that applications and software should also be energy-wise [HA09]. The architecture, design and implementation of a software has direct impact on the power consumed by underlying

platform [Min07]. This is also applicable for mobile applications which may adversely affect battery life of mobile devices. These days, developers are focusing on building more and more applications while paying little attention towards the battery consumption of their applications. Many of these applications continue running in the device background and novice users remain unaware of such activities. Proper guidelines and steps must be taken to spread awareness among developers and end-users regarding carbon footprints of energy inefficient applications and software.

It is important to focus on all of the above categories in order to obtain significant results from green computing initiatives. Several mechanisms are being introduced to promote energy efficiency in the ICT sector. Creating energy-efficient equipment, introducing sleep modes in devices and careful selection of energy sources are some such mechanisms [Sug12]. Mittal et al. [KM13] has reviewed several companies such as IBM, Dell, Microsoft, HP and major initiatives taken by them towards Green ICT. ICT sector can also be used to spread green computing awareness through information systems. It can play a key role in the development of intelligent processes for sustainable and environment friendly production and consumption of products [Ser12, HLH11].

## 2.2 Green Networking

Previously, it has been discussed that there is a need for greening of networks and their contribution is important for overall green ICT initiatives. Two main drivers of green networking are [BBDC11]:

- Environmental factors such as minimizing greenhouse gas emissions.
- Economic factors such as reducing the costs of power consumed by network infrastructure.

Telecommunication companies and ISPs are innovating new services and their customer base is rapidly growing [BBDC11]. Data traffic volumes are also multiplying [ZZY<sup>+</sup>08]. With these trends, telecommunication companies and ISPs require more number of network devices with higher capabilities to perform complex operations. Traditionally, these devices have been designed to handle peak loads and are normally under-utilized [BCRR12]. Their prime objective has been to provide better quality of service (QoS) and network reliability. In order to contribute to green networking, these devices should be designed to be scalable and have a better ratio of performance to energy consumption. It is challenging to design network infrastructure that is both energy-efficient and provides high QoS & reliability at the same time.

Researchers have proposed several schemes to promote energy efficiency in networks. Bianzino et al. [BCRR12] has classified these schemes into the following categories:

### ***Resource Consolidation***

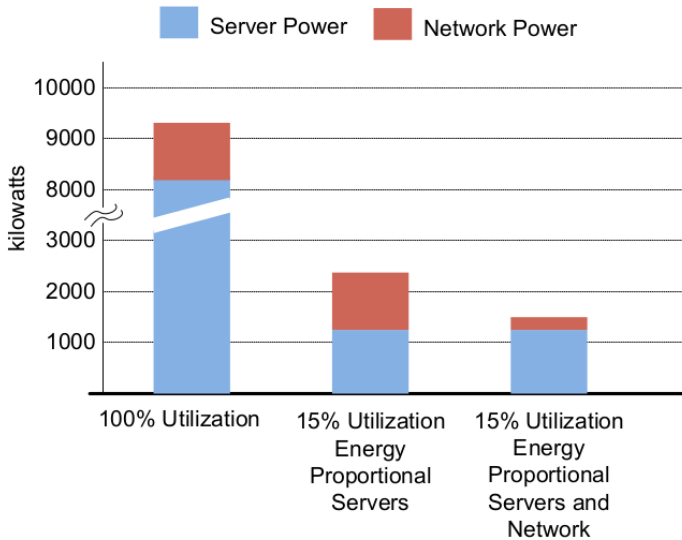
This set of solutions focus on turning-off network equipment, when not in use, without compromising network performance. One way to do this is by using intelligent routing algorithms [GMMO10, CEL<sup>+</sup>10]. Network traffic patterns can also be analyzed to provide dynamic provisioning of devices [MSBR09a]. Mahadevan et al. [MSBR09a] has claimed that up to 75 percent power savings could be achieved by incorporating network traffic management and server consolidation schemes. *Cisco Integrated Service Router* [Cis08] is an excellent example of this kind of energy-saving scheme. It reduces power consumption by integrating six different devices on a single platform, thereby, reducing the physical space requirements, cooling and energy costs by more than 76 percent.

### ***Virtualization***

Virtualization aims at maximizing hardware utilization by supporting multiple services on the same hardware. Virtualization can be implemented for network links, storage devices, software resources among other network components [BCRR12]. Chowdhury et al. [CB10] has surveyed various network virtualization techniques. The authors state that, “*by allowing multiple heterogeneous network architectures to cohabit on a shared physical substrate, network virtualization provides flexibility, promotes diversity, and promises security and increased manageability.*” Virtualization techniques in networks can also enhance their energy efficiency.

### ***Proportional Computing***

This solution can be implied to a complete system or to selected network devices or protocols [BCRR12, CCMM11]. Abts et al. [AMW<sup>+</sup>10] has discussed several ways to design a high-performance data center network whose power consumption is proportional to the amount of traffic. The authors have stressed on the fact that network consumes almost 50 percent of the power in data centers for energy proportional servers, as shown in Figure 2.2. Niccolini et al. [NIR<sup>+</sup>12] has proposed an idea to build a power-proportional router whose power consumption is proportional to its utilization. Likewise, innovative solutions can be adopted to improve the energy proportionality of other network devices and infrastructure as well. Energy proportionality should be considered as an important aspect of network equipment besides performance and reliability.



**Figure 2.2:** Comparison of Server and Network Power in Data Centers [AMW<sup>+</sup>10].

### *Selective Connectedness*

This technique works on similar grounds as resource consolidation. Allman et al. [ACNP07] has explored this solution where edge nodes are allowed to enter into low-powered states when they are *mostly-idle* while still retaining their connectivity to the internet. The authors state that this technique promises potential energy savings, however, can be very challenging to implement considering current state of the network infrastructure.

The above energy-saving schemes are being incorporated by ICT based industries to promote green networking. One example is the technology initiative taken by Qualcomm<sup>2</sup> to manufacture energy-efficient hardware [Qua] for devices such as home routers, gateways and Ethernet solutions complying with *IEEE 802.3az Energy-Efficient Ethernet (EEE)* standard [CRN<sup>+</sup>10]. *Green BitTorrent* [BC09] is another such initiative. Peers advertise their energy-states and prefer downloading chunks from active peers compared to idle ones. Such recent developments in the area of green networking support that one can gain considerable power savings by adopting

<sup>2</sup><http://www.qca.qualcomm.com>

energy-saving mechanisms. These mechanisms can be expected to become an inherent and essential component of network infrastructure in coming years.

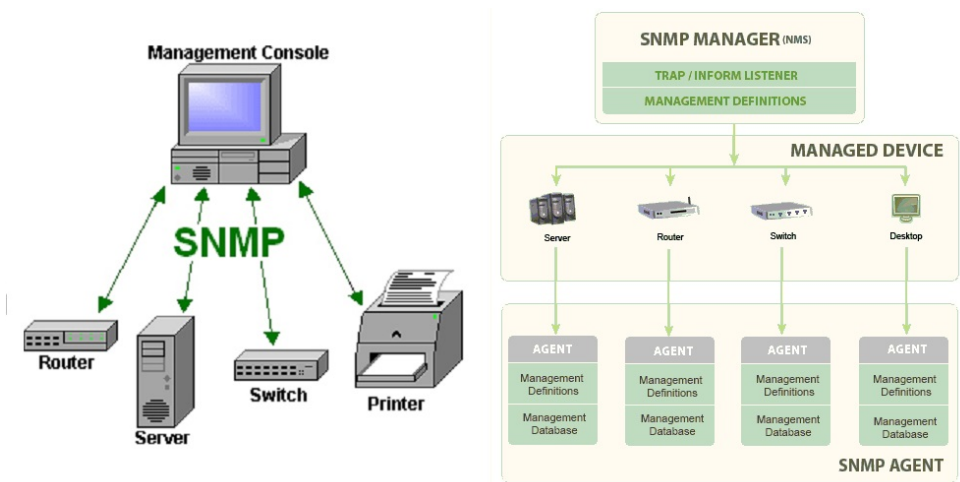
### 2.3 Estimation of Network Power Consumption

In order to promote and implement network power saving mechanisms, some efforts have been directed towards power modeling and measurements of networks. These techniques are necessary to evaluate the performance of green initiatives. Several researchers have attempted to estimate power consumption in networks [BHT07b, HBF<sup>+</sup>11, TBA<sup>+</sup>08, CK06, CSB<sup>+</sup>08, MSBR09b, MSBR09a]. When we use the term "Networks", it has a very broad meaning. Networks may be split into three logical layers namely core network, access network and metro network [BHT07a]. Core network builds up the mesh backbone of internet while access network connects end users to the network. Metro network acts as an interface between access network and core network to handle fluctuating traffics from end users. The division of networks into logical layers or components can be helpful in performing network power estimations more efficiently.

#### *Network Energy Monitoring using SNMP*

Simple Network Management Protocol (SNMP) is a set of protocols for managing complex networks. SNMP consists of a set of standards for network management, including an application layer protocol, a database schema, and a set of data objects [HPW02]. SNMP components are shown in Figure 2.3. An SNMP Manager runs a Network Management System (NMS) to manage network devices through SNMP Agents. The Agents collect information from network devices and deliver it to the Manager which stores them in a database. SMTP Manager uses a virtual database known as Management Information Base (MIB) [GO90] to request agents for specific information.

Some network power monitoring and management schemes have been proposed by researchers based on using MIB to capture relevant attributes related to energy consumption of network devices. Almqvist et al. [AW94] is one of the earliest works which proposed a scheme for standardizing energy management in networks using SNMP interface. It discusses the functional and implementation aspects of using the SNMP interface for management of energy networks and suggests the idea of Energy Management Information Base (EMIB) as an extension of MIB dedicated to energy management. Another recent work by the Internet Engineering Task Force (IETF) has defined a subset of MIB for power and energy monitoring of network devices [Ver11]. Blanquicet et al. [BC08] and Jain et al. [JPBM10] have also proposed energy consumption models based on EMIB.



**Figure 2.3:** Components of Simple Network Management Protocol [Inn].

The existence of network power modeling and measurement techniques is important for accurately estimating the energy efficiency of networks. They also play a significant role in testing the usability of various green networking initiatives.





# Chapter 3

## Packet-Level Energy Accounting

This chapter provides a conceptual overview of the idea of packet-level energy accounting which is the basis for this master thesis. It also explains various use cases where this concept can be implemented to promote green networking.

### 3.1 Conceptual Overview

Siekkinen et al. [SNYJ12] has proposed an idea of accounting energy consumption of networks using packet-level energy accounting. The idea is to add a cumulative energy counter to each packet. As a packet traverses through the network, this counter is updated by each network device on its route. This update is based on the amount of energy spent by a device in order to process the packet. The route can comprise of both energy-efficient as well as energy-inefficient network devices. When a packet arrives at its destination, energy counter values can be used to obtain relevant energy-related information. By analyzing this information, it may be possible to infer the energy efficiency of a network route or even overall energy consumption of a network. For example, destinations can be made aware of their carbon footprint involved in accessing the network.

The proposed concept [SNYJ12] specifies two approaches to calculate per-packet energy counter values.

**First approach** suggests periodically calculating and updating energy counter values. Each network device calculates the value based on the energy it consumes in order to process incoming traffic flow within a certain time period. These pre-computed values are added to each incoming packet within the next time period. The values are calculated based on a traffic flow instead of an individual packet. It is important to decide a suitable time interval for updating these energy counter values. A longer time period will result in lesser impact of sudden traffic bursts on the values compared to a shorter time period. The durations can vary depending

upon the use case where this concept is applied.

**Second approach** calculates and updates energy counter values for each incoming packet. Unlike the first approach, network devices are not required to store any traffic flow related information for any period of time. This approach appears to be more accurate as it is able to capture the impact of minor traffic fluctuations in the network. However, it may prove to be computation intensive for networks with high packet arrival rates. Moreover, in case of the networks where traffic rate does not fluctuate frequently, energy counter values may not vary for each packet. Once again, selection between the two approaches can be made based on the use case.

This energy accounting mechanism can also be extended to different network layers [SNYJ12]. Energy spent on processing a packet between any two network hops is a contribution of each layer in the network stack. Furthermore, there is also a possibility to include application-level energy accounting [SNYJ12].

## 3.2 Use Cases

Siekkinen et al. [SNYJ12] has analyzed a few use cases where the idea of packet-level energy accounting can be implemented to achieve power savings. It can be useful in areas such as network traffic engineering or energy optimization of networks. This section discusses some of the use cases.

### *Aid in Network Traffic Engineering*

Traditional network traffic engineering schemes did not take into account the power consumption factor [ACE<sup>+</sup>02]. They mainly focused on network load balancing, fault tolerance and QoS. Recent research works have proposed optimization methods for traffic engineering which are mainly based on resource consolidation or power proportionality of network devices. However, most of these proposals can only be deployed centrally within a network domain. They do not support inter-domain traffic management.

On the other hand, packet-level energy accounting can enable distributed solutions supporting both intra-domain and inter-domain traffic optimizations. The energy counter values can be added to IPv6 packet header extension or IPv4 optional header fields. Packets can collect and convey energy related information across multiple networks. This can lead to intelligent traffic engineering schemes without compromising network performance.

### *Energy Awareness of End Users*

With cheaper access to internet, end users are mainly concerned with network QoS and availability. As long as they have access to internet, they do not pay much attention to the carbon footprint of their actions while accessing internet services. Packet-level energy accounting based mechanisms can be used to bring awareness among end users. They could be provided with greener alternatives to use internet services. This scheme can also be used to promote sustainable products which users may favor over non-green alternatives [EW09].

### *Server Selection in Content Delivery Networks*

One of the use cases of this model is server selection in Content Delivery Networks (CDNs). A CDN consists of several mirror servers, storing copies of content and distributed over several geographical locations. A client requests content from a content delivery service. Based on the location of client's local DNS, a nearest server is normally assigned to address the client's requests. However, server selection could also be based on several other attributes such as end-to-end response time, least loaded server or minimum energy spent during the content transfer. Packet-level energy accounting can be used to calculate most energy-efficient server that can be assigned to deliver content to a client. This use case has been further analyzed in this master thesis.

The concept of packet-level energy accounting can create energy incentives for ISPs and can also be used in mechanisms to reduce network energy consumption. The thesis work focuses on the design and implementation of an energy accounting model based on this concept. It is important to design the model in such a way that it can be implemented for multiple use cases with minimum adjustments and reforms.



# Chapter 4

## Energy Accounting Model

This chapter describes the energy accounting model that has been implemented in this master thesis. Before that, it discusses the design challenges and goals of the model that will be helpful in analyzing its implementation feasibility.

### 4.1 Model Design Challenges and Goals

In order to implement the model, it is necessary to assess the challenges involved in designing the model and goals of this model.

When a packet is routed through a network, the following two scenarios may occur.

**Scenario 1:** The packet has a choice to traverse a network route with energy-efficient network devices compared to another route with energy-inefficient network devices.

**Scenario 2:** A packet has more than one route to destination, where both the routes have energy-efficient network devices.

In first scenario, the energy counter values should enable us to assess the energy efficiency of the network route traversed by a packet. We should be able to distinguish between packets traversing more energy-wise routes from those following less energy-wise routes. The term *energy-wise* is synonymous to the term *energy-efficient*. If a network device is termed as either energy-wise or energy-efficient, it means that the amount of energy consumed by the device is proportional to its utilization. Such devices consume least amount of energy when idle and highest energy when working at peak load. The model should promote energy efficiency irrespective of the length of a route. It is not necessary that a shorter route will always consume less energy. A longer route with more energy-wise devices can be more energy-efficient compared to a shorter route with less energy-wise devices.

In second scenario, the model should also take into account network performance metrics such as network throughput, to promote efficient routes for a packet. For example, if one of the routes is highly congested while another route is not congested, the latter should be preferred. The model should promote energy-efficiency but not at the cost of network performance. This is important for the feasibility of the model in real world scenarios. There can be a trade-off between energy-efficient network routes and high performance routes. The model should adopt a balanced strategy in order to be more effectively integrated with existing network implementations.

One important challenge in formulating the energy accounting model is the distribution of idle power consumption of network devices among network traffic. Currently, the amount of power consumed by network devices is not proportional to the amount of incoming traffic. Their Energy Proportionality Index (EPI) [MSBR09b] values are very less [SNYJ12]. High idle power consumption reflects the energy inefficiency of these devices. The model should ensure that each packet suffers equally when forwarded through such devices having a high idle power. When packets are processed by devices, their idle power factor should be added to the energy counter values of all incoming packets. Devices with higher idle powers should result in higher counter values compared to those with a lower idle power.

The energy model should be implemented without major resource requirements and without degrading network performance and throughput. The method of energy accounting needs to be fool proof in scenarios where the aim is to provide incentives to more energy-efficient network service providers. In those cases, it should not be possible to easily manipulate the ways in which energy accounting is carried out. In general, the model should always reflect accurate results from which proper inferences could be drawn regarding the energy efficiency of a network.

Several challenges and goals have been mentioned that should be addressed by this energy model. Main aim of this model is to accurately calculate the energy spent by a network to process each packet that is routed through it. It is important to appropriately recognize all the factors that may impact per packet energy values.

## 4.2 Model Description

This section describes in detail, the approach to calculate per packet energy consumption values. When a packet originates from a source, information related to energy consumption for processing the packet is added to its IP header. As the packet traverses through the network, routers calculate and update these energy values before forwarding it to the next hop. When a packet is received by its destination, the final values can be analyzed to obtain energy-related information. The main challenge is to accurately estimate the amount of per-packet energy consumption

and define a mechanism to calculate energy counter values.

In this model implementation, routers calculate and update energy values for each incoming packet instead of updating the values periodically. This method is preferred as it does not require routers to store information about incoming traffic over a period of time. Rather, it simplifies router operations. In order to calculate the energy spent by a router to process each incoming packet ( $E_p$ ), router's instantaneous power consumption ( $P_t$ ) needs to be estimated. Then, this power is fairly distributed among all the incoming packets at that instant. Here is a step by step explanation of the process.

**Step 1: Calculate router utilization at any instant ( $U_t$ )**

In order to calculate instantaneous router power consumption,  $P_t$ , router utilization at that instant must be known. Router utilization can be expressed as a ratio of instantaneous packet arrival rate ( $\lambda_t$ ) to average packet processing rate of the router ( $\mu$ ) as given by Equation 4.1. Both  $\lambda_t$  and  $\mu$  are expressed in bits per second (bps). Here, router utilization is calculated for each incoming packet.  $\lambda_t$  is calculated for the current packet and the previous packet processed by the router as given by Equation 4.2. It is different from the average packet arrival rate of the router which is averaged over all packets arriving in a certain time interval.

$$U_t = \lambda_t / \mu \quad (4.1)$$

$$\lambda_t = S / I_t \quad (4.2)$$

$\lambda_t$  is the instantaneous packet arrival rate (in bps).

$\mu$  is the average packet processing rate of the router (in bps).

$S$  is the size of each incoming packet (in bits).

$I_t$  is the time elapsed since the last packet arrival.

**Step 2: Estimate router power consumption at any instant ( $P_t$ )**

It can be very challenging to estimate the amount of power consumed by a router to process an incoming packet at any given time. Normally, energy-inefficient routers operate at a maximum power irrespective of traffic arrival rate or amount of router utilization, as depicted in Figure 4.1. However, with trends favoring green networking, we can predict that, in the near future, router power curves will vary with percentage utilization of routers at any instant of time. This variation can be linear as depicted in Figure 4.2 and defined by Equation 4.3.

$$P_t = k * U_t + b \quad (4.3)$$

$$= (P_{max} * \min(T_{out}, I_t) + P_{min} * \max(0, I_t - T_{out})) / I_t \quad (4.4)$$

$$= P_{max} - e^{U_t/\alpha} * 0.95 * P_{max} \text{ [Sev12]} \quad (4.5)$$

$P_t$  is the power consumed by a router at any time instant  $t$  (in Watts).

$P_{max}$  is the maximum power a router can consume at peak load (in Watts).

$P_{min}$  is the idle router power or the power consumed in sleep state.

$T_{out}$  is the sleep interval or time-out interval of a sleep on-off router.

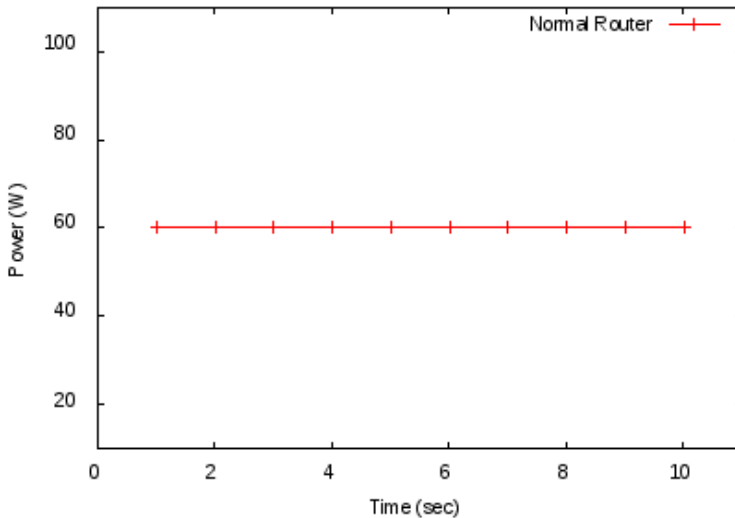
$I_t$  is the time elapsed since the last packet arrival.

$U_t$  is router utilization at any time instant  $t$ .

$\alpha$  is the coefficient that defines how quickly the power converges to its maximum value.

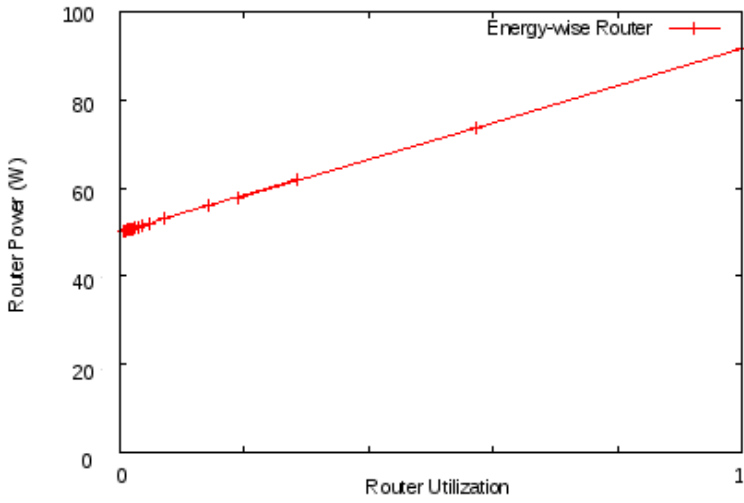
$k$  and  $b$  are router specific constants.

Energy-efficient routers may have an irregular power curve or an exponential curve. The curve depicted in Figure 4.3 represents a sleep on-off router having a sleep state. Its power curve can be defined by Equation 4.4. If the time interval between any two incoming packets exceeds the sleep interval of the router, it enters into sleep state. Such kind of routers are very energy-efficient, however, a lot of energy might be required to wake up a router after it enters a sleep state. Lastly, the curve depicted in Figure 4.4 represents a scenario where router power increments in steps with increase in utilization. This can be due to some energy saving mechanisms implemented in a router which does not allow an immediate increase in router power. The power curve later converges to the device maximum and can be defined by the Equation 4.5.

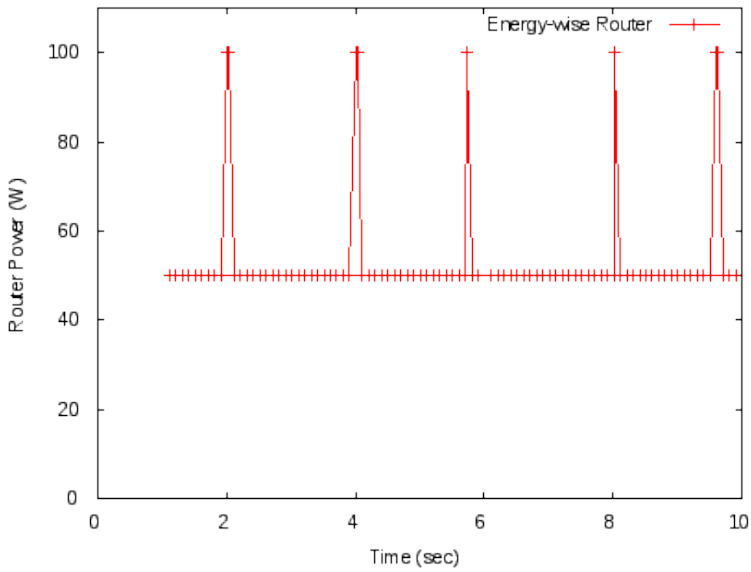


**Figure 4.1:** Constant Power Router.

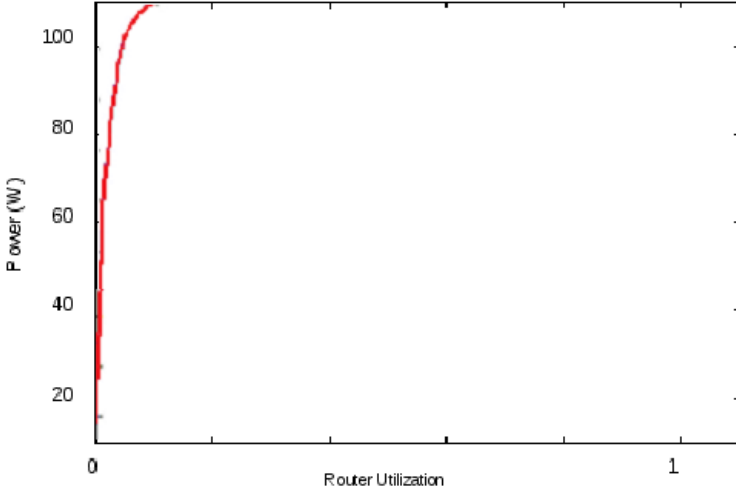




**Figure 4.2:** Linear Power Router.



**Figure 4.3:** Sleep On-Off Router.



**Figure 4.4:** Exponential Power Router.

**Step 3: Calculate router energy consumption for packet arriving at time instant  $t$  ( $E_t$ )**

Energy spent by a router for processing incoming traffic can be given by Equation 4.6.

$$E_t = P_t * A_t \quad (4.6)$$

$$A_t = \alpha * \delta + (1 - \alpha) * A_{t-1} \quad (4.7)$$

$$E_t = (k * U_t + b) * A_t \quad (4.8)$$

$$E_{idle} = b * A_t \quad (4.9)$$

$A_t$  is the average inter-arrival time between packets at the instant  $t$ .

$\delta$  is the sampling period over which we can average the value of  $P_t$ . However, in this implementation,  $\delta$  is the same as  $I_t$ .

$\alpha$  decides the sensitivity to changing load. Higher values of  $\alpha$  increases the sensitivity while lower values reduce it.

If a linear power router is used, the value of energy spent by the router for each incoming packet can be obtained by substituting the value of  $P_t$  from Equation 4.3 in Equation 4.6. The resulting value given by Equation 4.8 is the total energy spent by a linear power router to process a packet incoming at time instant  $t$ . This value includes the idle router energy consumption factor  $E_{idle}$ . In case, there is no incoming

traffic and router utilization is zero, router still consumes a minimum idle energy given by Equation 4.9. The energy consumed by a router at any instant will always be greater than idle router energy consumption ( $E_{idle}$ ).

The energy accounting model implemented in this thesis follows the step-by-step approach described above to compute energy estimations in networks. These estimations can be used to analyze various use cases of the model.



# Chapter 5

## Simulation Results and Analysis

The previous chapter provided a theoretical description of the energy model. However, a theoretical model is not sufficient to justify its usability in real world scenarios. In order to estimate power gains that can be obtained through this model, it is implemented in NS-3 simulator for the use case of selecting energy-efficient servers in Content Delivery Networks (CDNs). The use case has been briefly discussed in Section 3.2.

Whenever a client requests content from a CDN, several mirror servers in the CDN are capable of delivering content to the client. However, in normal circumstances, a server that is geographically closest to the client is assigned to respond to the client's request. Sometimes, if the nearest server is overloaded with requests, another server is assigned to the client so that the QoS of content delivery is not compromised. However, energy-efficiency is not a priority in the functioning of CDNs.

In this thesis, instead of assigning CDN servers to clients on the basis of geographical location or QoS, they are assigned based on the amount of energy consumed in the network to process a client's request. A server is selected such that the overall power consumption of the network is minimized. Several servers can be available for processing an incoming client request. For each of these servers, the power required to deliver content to the client may vary. Clients are made aware of the power consumption for accessing content from these server alternatives. The clients can then choose a server that satisfies the following terms of service:

- Out of all available server alternatives, if content is delivered using the selected server, there is a minimum increase in the overall power consumption of the CDN.
- QoS of the content delivery service is not compromised.
- Network dynamics are taken into consideration. There should be a possibility to switch to another server alternative in the CDN, if QoS provided by current

server decreases due to network dynamics or other factors.

This section proposes an energy accounting protocol that utilizes the original idea of packet-level energy accounting for the use case of selecting energy-efficient servers in CDNs. The energy model is used to perform power estimations for different simulation scenarios and network topologies. The idea is to embed information in packets sent from each server to the client. It is challenging to decide what details should be embedded in each of these packets. The effect of random traffic in the network due to other clients simultaneously accessing the CDN should also be considered.

## 5.1 Energy Accounting Protocol v1.0

This section presents the energy accounting protocol that is designed for analyzing the use case of CDNs. As mentioned previously, instead of assigning CDN servers to clients on the basis of geographical location or QoS, they are assigned based on the amount of energy consumed in the network to process a client request. The process involves the client sending probe requests to possible server alternatives in the CDN. Each server responds with a probe response which consists of a packet train. The packets in the probe response capture information about the power consumption in the CDN which may occur due to content delivery between the client and the respective server who sends the probe response. When a client has received probe responses from all server alternatives, it then selects the server that will result in least power consumption to deliver content to the client.

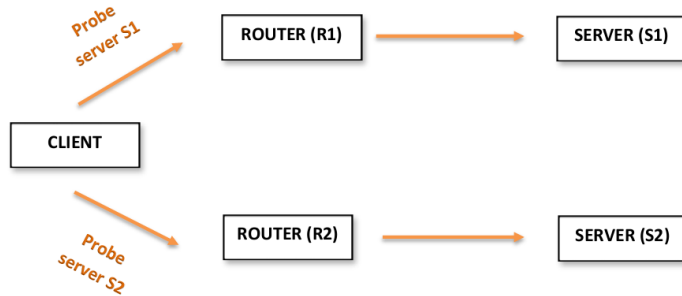
In this protocol, each CDN client sends probe packets to servers in the CDN when it initiates a content delivery request. In response, each server sends back a packet train to the client. This train consists of up to 1000 packets sent at a constant rate by the server. The reason of sending a 1000 packet long train is that it acts as dummy content that is delivered from the server to client and it helps in providing an estimate of the network power consumption which may occur as a result of actual content delivery between the client and the server. This process is depicted in Figure 5.1.

Using the energy accounting model, the following information is added to each packet in the response train.

- $\Delta E_t$ : The amount of energy consumed by routers on the path from server to client in order to process the packet.
- *Hops*: Number of hops traversed by the packet.

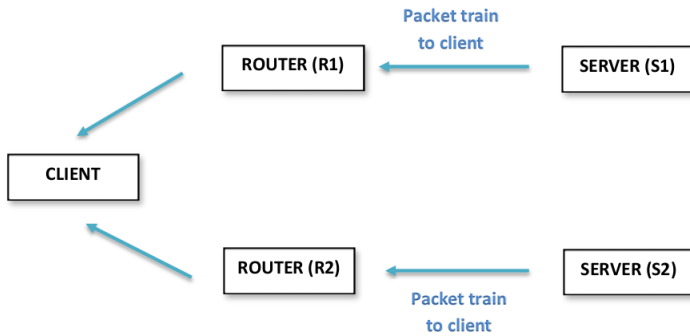
If  $E_t$  is the energy consumption of a router at time instant  $t$  and  $E_{idle}$  is the energy consumption of router in idle state with no incoming traffic, then,  $\Delta E_t$  can be expressed as in Equation 5.1.  $E_{idle}$  factor is subtracted as it does not contribute to the router energy variations due to newly incoming traffic. Hop count is included in each packet to calculate energy values per hop. This is necessary to mitigate the effect of routing protocols and path lengths on the energy consumption values. Each router, on the path between server and client, calculates its instantaneous utilization and energy consumption for every incoming packet. It then updates the  $\Delta E_t$  value and increments the *Hops* field for each packet before forwarding it.

$$\Delta E_t = E_t - E_{idle} \quad (5.1)$$



STEP 1: CLIENT PROBES EACH CONTENT SERVER

(a) Client Probing Content Servers



STEP 2: EACH SERVER RESPONDS WITH A PACKET TRAIN TO CLIENT

(b) Servers Responding with a Packet Train to Client

**Figure 5.1:** Simulation Scenario.

When a client receives the packet train from all the server alternatives in the CDN, it is able to extract the average energy consumption values from their responses. The client can then choose to continue with the best alternative available at that time. The main concern is to accurately predict the energy consumption in CDN due to the newly initiated communication between a CDN server and a client. These energy consumption values help in predicting the amount of energy that will be consumed in case of content delivery from the server to the client. Therefore, efforts can be made to choose the most energy-efficient server.

Several test cases have been simulated to test this protocol. The aim is to analyze the impact of different factors on per-packet energy consumption in CDNs.

### 5.1.1 Simulation Scenario

The network topology used for this simulation is depicted in Figure 5.1. It consists of a simple network with a single client, two routers and two servers. In this topology, routers R1 and R2 are modeled to have different power curves and behave differently under similar network conditions. No external traffic is introduced into the network. This is a hypothetical scenario which makes it convenient to assess the usefulness of our energy model. Both servers S1 and S2 behave identically.

The client receives packet trains, one each from server S1 and S2. Based on power curves of routers R1 and R2, packets in both trains have different energy counter values. These values also vary with packet sending rate controlled by each server, router performance and packet sizes. The simulations try to study the impact of these factors on the energy counter values in packets. The goal is to assess the usefulness of the energy model in this simplest CDN scenarios and get useful information from the packet trains to help the client to choose a suitable CDN server.

### 5.1.2 Observations

With no external traffic, the routers remain under-utilized, that is utilization,  $U_t < 1$ . Routers are still utilized by the probe response packets. Therefore, they are not completely unutilized.

**Case 1: Router R1 is modeled as a constant power router (refer Figure 4.1). Packet trains are sent from server S1 to the client.**

In this case, the router is already operating at a constant maximum power. Router power consumption remains unchanged due to the communication between server S1 and the client.  $\Delta E_t$  value is recorded as null for each packet in the train. If the client selects server S1 for content delivery, the overall energy consumption of the network will remain unchanged.



**Case 2: Router R2 is modeled as a linear power router (refer Figure 4.2). Multiple packet trains are sent from server S2 to the client. Each packet train is sent with a different packet rate. However, the rate is uniform for all the packets within a train.**

In this case, it is observed that, irrespective of the packet sending rates, energy required to process each packet remains the same over multiple packet trains. The amount of energy spent by the router to process packets depends only on the packet size and router's packet processing capacity. It is independent of the rate at which packets are sent by the server as long as they are equally timed when they are received by the router. The observations are also mathematically verifiable and for a linear power router, the value of  $\Delta E_t$  reduces to Equation 5.2.

$$\Delta E_t = k * S / \mu \quad (5.2)$$

k is a router constant.

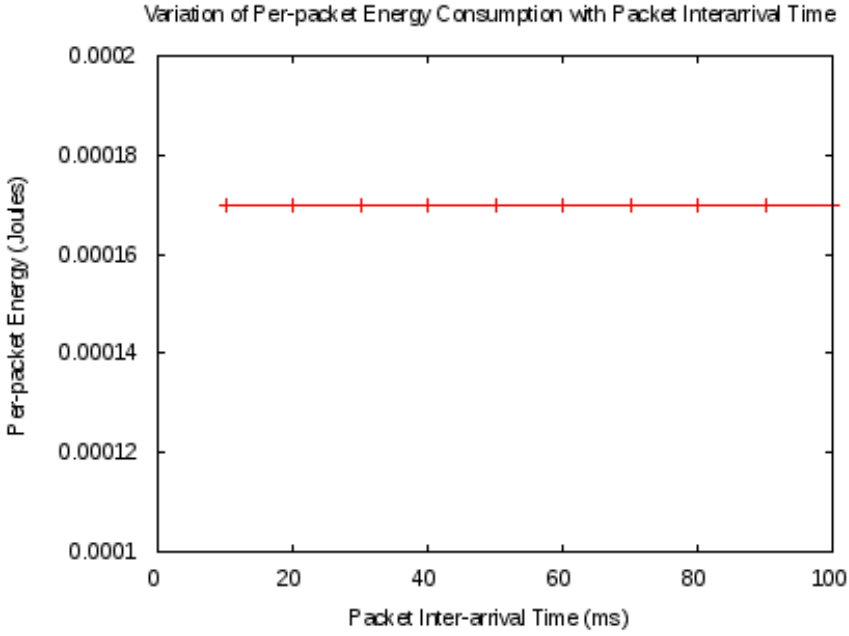
S is the size of each incoming packet (in bits).

$\mu$  is the average packet processing rate of the router expressed in bits per second (bps).

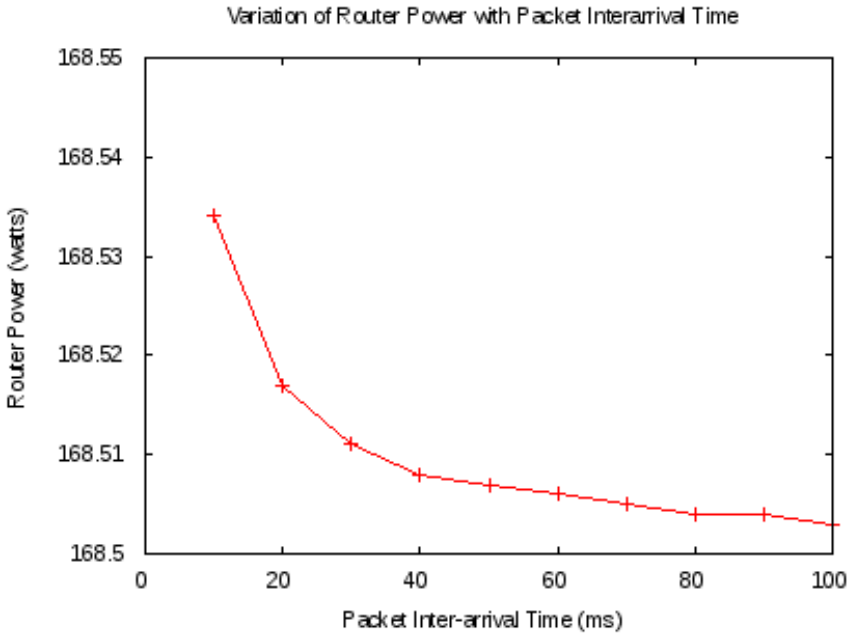
Simulation results are depicted in Figure 5.2. Figure 5.2(a) shows that per-packet energy consumption remains constant with varying packet inter arrival time. Packet arrival rate, router utilization and router power decrease with increase in packet inter arrival time.

**Case 3: Router R1 is modeled as a sleep on-off router (refer Figure 4.3). Multiple packet trains are sent from server S1 to the client. Each packet train is sent with a different packet rate. However, the rate is uniform for all the packets within a train.**

Router R1 is simulated to have a sleep time-out of 50ms corresponding to packet rate of 20 packets/second. Simulation results are depicted in Figure 5.3. Figure 5.3(b) represents the effect of varying packet sending rate on the router power consumption. Router power increases linearly with increasing the packet rate up to 20 packets/second. Beyond that, the router consumes a constant maximum power. Figure 5.3(a) depicts the variations in per-packet energy consumption of the router with packet sending rate.

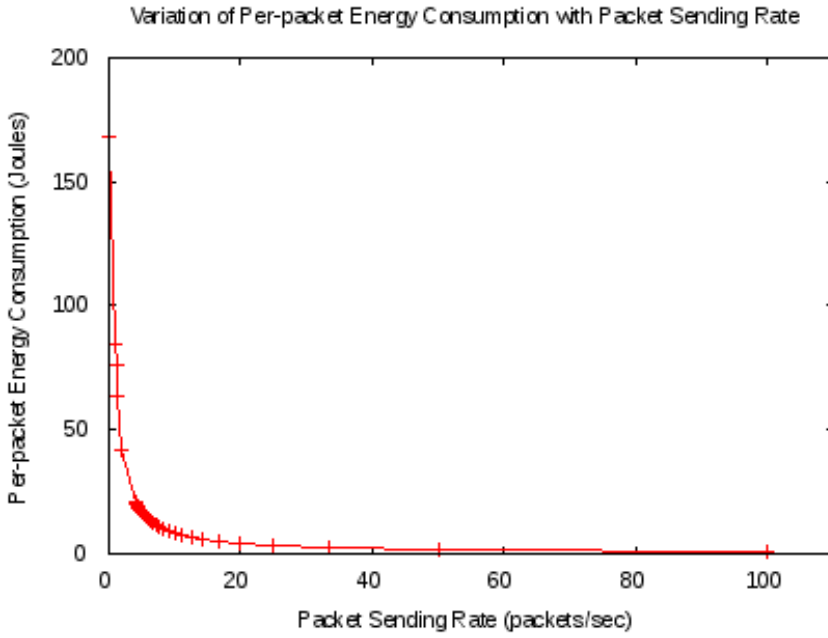


(a) Per-packet Energy Consumption

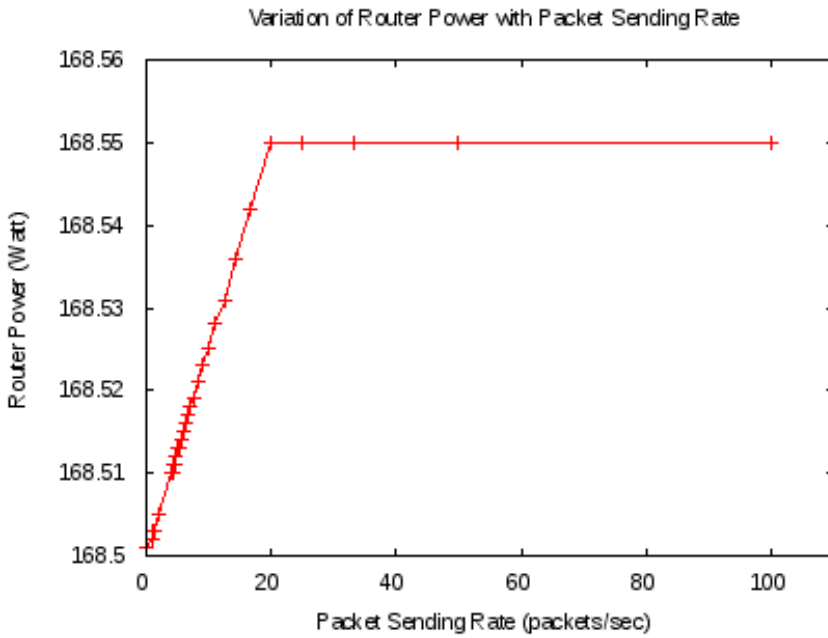


(b) Router Power Variation

Figure 5.2: Impact of Varying Packet Sending Rate on Linear Power Router.



(a) Per-packet Energy Consumption



(b) Router Power Variation

Figure 5.3: Impact of Varying Packet Sending Rate on Sleep On-Off Router.

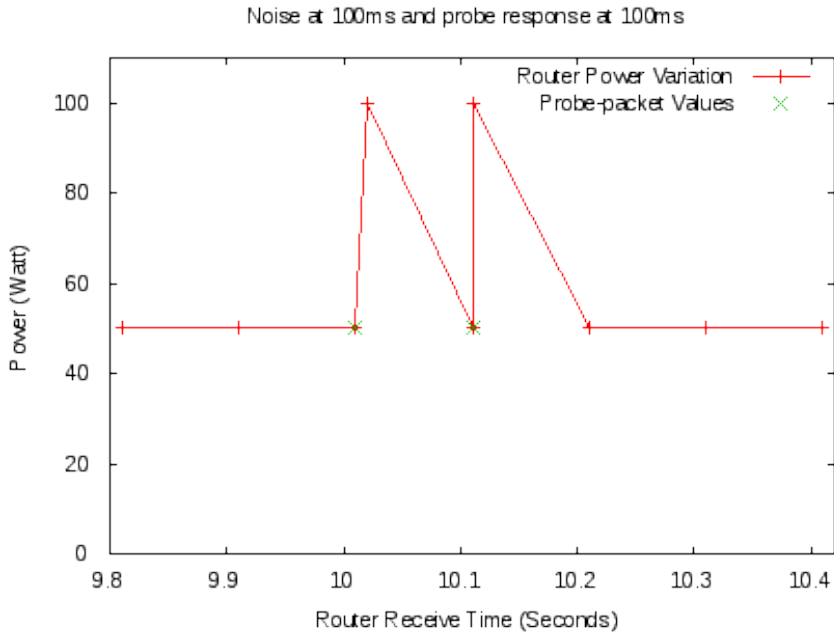
### 5.1.3 Analysis

In the above simulation, three different types of routers are compared under similar network conditions. In case of constant power router, there is no increase in energy consumption with increased traffic. In case of linear power router, total energy consumed by the router increases linearly with rise in incoming traffic. However, per-packet router energy consumption remains unchanged. As traffic increases, more energy is consumed but it is fairly distributed among more number of incoming packets. In case of sleep on-off router, it behaves as a combination of linear and constant power router. It acts like the former when packet arrival rate is slower than the sleep rate and consumes constant power beyond the sleep rate.

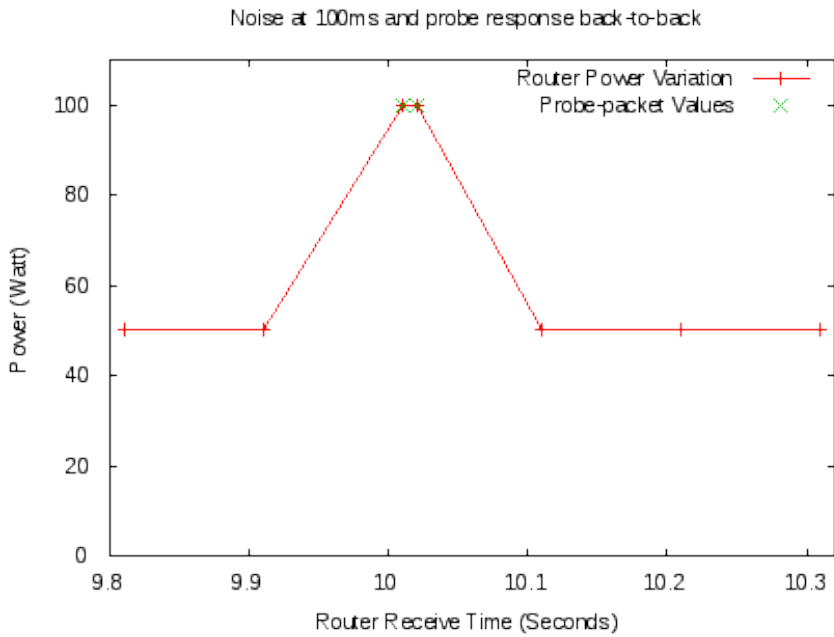
This simulation provides some information about the factors affecting router power variations for different router types. However, the information embedded in packets,  $\Delta E_t$ , is not sufficient to estimate the increase in router power due to newly initiated client-server communication. Among the three routers compared above, clients will prefer the route using constant power router over a sleep on-off router as  $\Delta E_t$  is higher for sleep on-off router. However, in cases of irregular network traffic, the values of  $\Delta E_t$  can also be negative. This happens when the network energy consumption decreases due to reduction in traffic at some point of time and it becomes difficult to compare  $\Delta E_t$  values for longer routes and multiple server alternatives. Therefore, the scheme may not work in complex network scenarios. Moreover, the packet train is not required to be 1000 packets long to convey information to the client. The next section discusses a more refined version of this protocol which addresses these issues.

## 5.2 Energy Accounting Protocol v2.0

Based on the analysis of previous implementation, there is a need to change the information embedded in the packet train from servers such that they convey relevant information to the client. In this version of the protocol, each CDN server sends two response packets to the client instead of a 1000 packet long response train. The probe packets should be sent such that they are able to capture the variations in power of routers on the route between client and server. The captured power variation should only be due to the newly initiated client-server communication. The change in number of packets from 1000 to 2 in the packet train is to reduce the probing overhead. In the previous protocol implementation, a 1000 packet long train was found to be unnecessary to capture power variations and the same task could be accomplished using a 2 packet long probe response.



(a) Server Response Packets with a Time Gap.



(b) Server Response Packets sent Back-to-Back.

**Figure 5.4:** Router Power Variations for Different Methods of Sending Server Response Packets.

There are two ways of sending the two-packet long server response to client:

- Sending both the packets back-to-back.
- Sending packets with a time gap in between the packets.

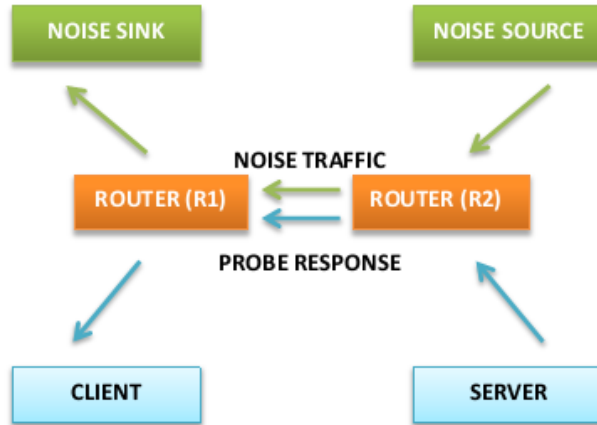
If response packets are sent with a time gap, it is observed that they are not able to capture router power variations due to the client-server communication. The observations in Figure 5.4(a) shows power variation of a sleep on-off router due to server response. The changes in router power due to first response packet are the same as due to the second packet. Both the packets capture the same value of router power. Moreover, even if the packets are sent back-to-back, they record router power variation after the packets have been received by the router, as shown in Figure 5.4(b). They do not provide any information about router's power prior to receiving server's response. Hence, in this implementation, it is still not possible to calculate the impact of client-server communication on the variation in router power consumption in a CDN.

The protocol needs to be modified such that the first packet records router power prior to its arrival. The second packet records the new router power value after arrival of first response packet. When both the packets reach the client, it can compute the amount of increase in router power as a result of the newly initiated client-server communication. This computation can be performed for each server alternative in the CDN. This modified protocol is further simulated for different CDN topologies and traffic scenarios.

### 5.2.1 Simulation Scenario 1

In this scenario, a simple CDN topology has been selected as shown in Figure 5.5. The topology consists of a client-server pair, a noise source-sink pair and two routers, R1 and R2. Only router R1 is modeled to update energy counter values in incoming packets. Router R2 acts as a normal router for simply forwarding the packets.

Router R1 is modeled as a linear power router and a sleep on-off router for different runs of the simulation. Both router types are compared under similar noise traffic conditions and both have a power range from 0 - 100 Watts for ease of comparison of results. Noise source is modeled to send a continuous stream of traffic to the sink. This stream is intended to interfere with the server response packets sent from server to client. As soon as router R1 receives those response packets, there is a sudden surge in its power which is recorded in the packets. The amount of power variation differs for linear power router and sleep on-off router.



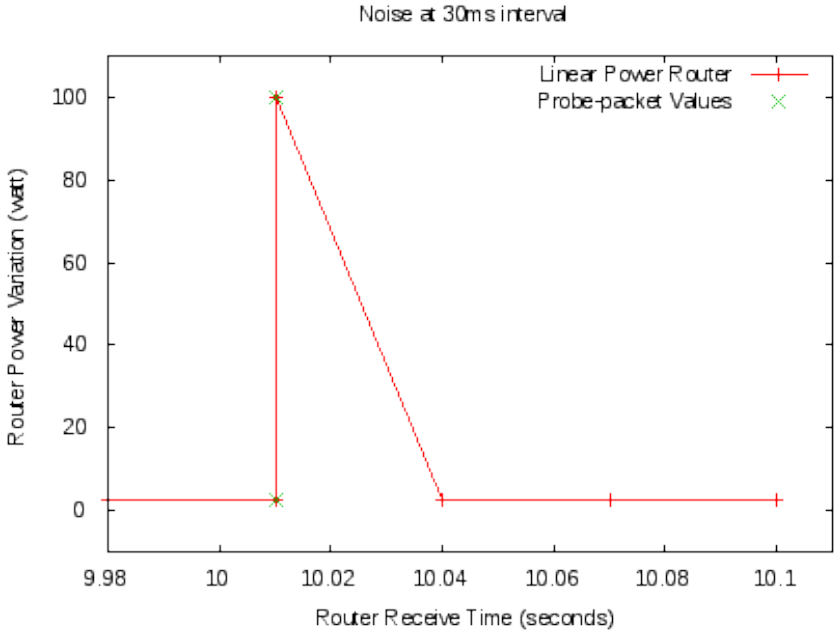
**Figure 5.5:** Simulation Scenario: Topology with a Single Energy-wise Router.

### 5.2.2 Observations

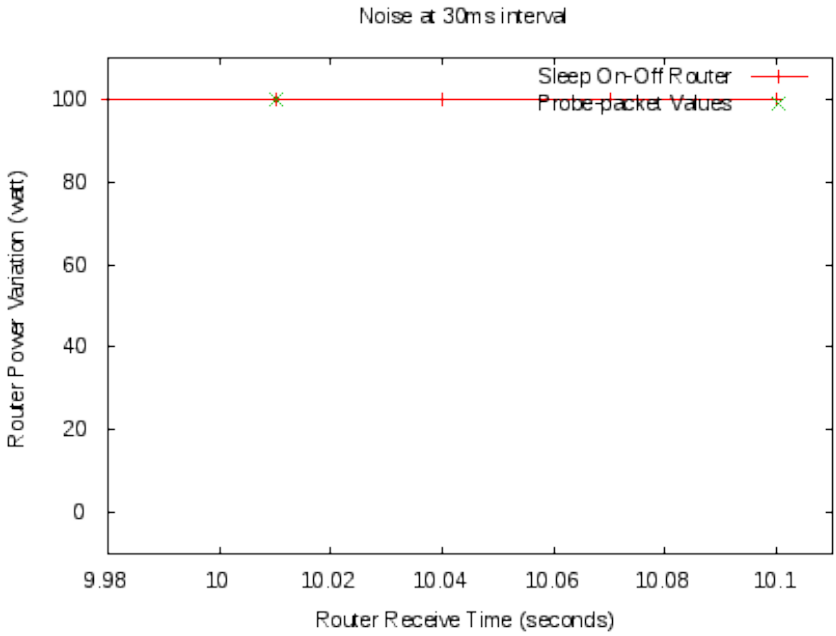
Simulation results are depicted in Figures 5.6 - 5.9. Each figure shows the comparison of a linear power router and a sleep on-off router under similar noise traffic. It can be observed that linear power router operates at a lower power level compared to a sleep on-off router. Due to arrival of back-to-back server response packets, routers experience a sudden surge in power consumption.

In case of linear router, its power increases linearly with increase in router utilization. Its behavior at different noise traffic levels is shown in Figures 5.6(a), 5.7(a), 5.8(a) and 5.9(a).

The sleep router is modeled to have a sleep time-out of 50ms. If noise traffic interval is less than 50ms, it consumes a constant maximum power, as shown in Figure 5.6(b), for 30ms noise traffic interval. It behaves similar to linear power router for noise intervals greater than its sleep time-out of 50ms. These cases are shown in Figures 5.7(b), 5.8(b) and 5.9(b).



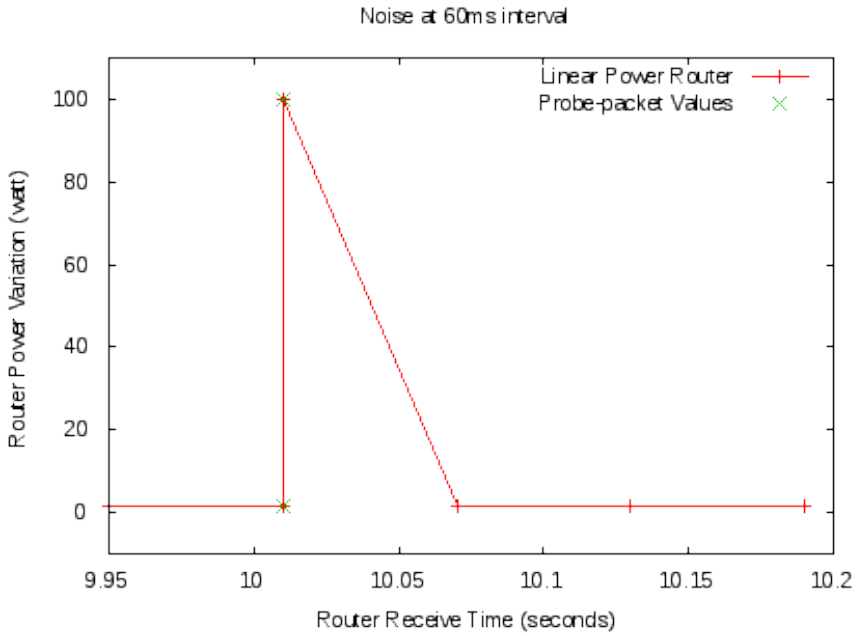
(a)



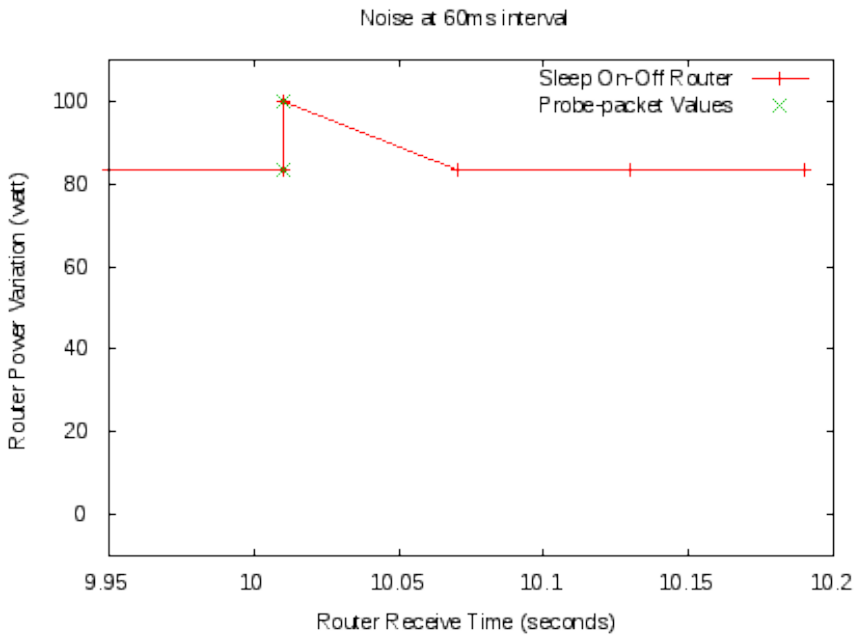
(b)

**Figure 5.6:** Router Power Variations for Linear Power Router and Sleep On-Off Router with Constant Noise Traffic at 30ms Interval.



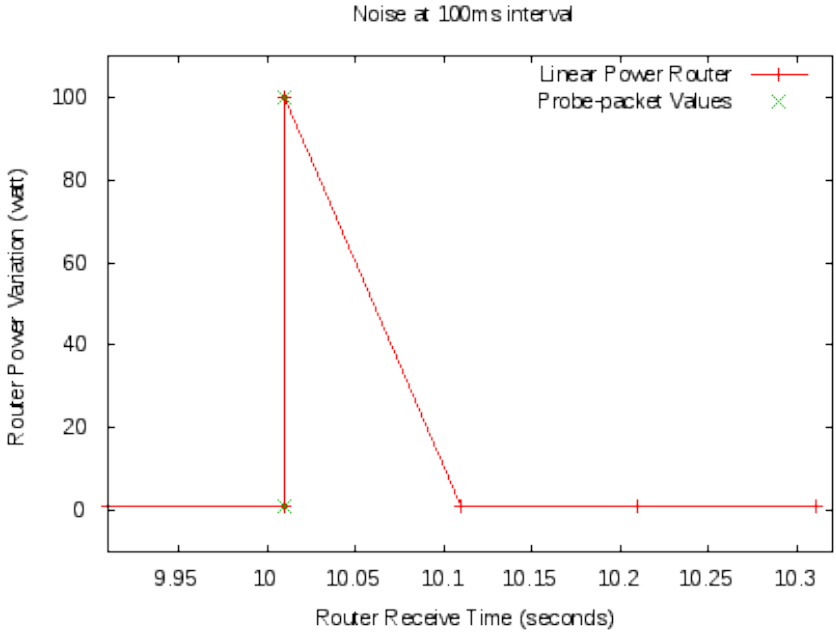


(a)

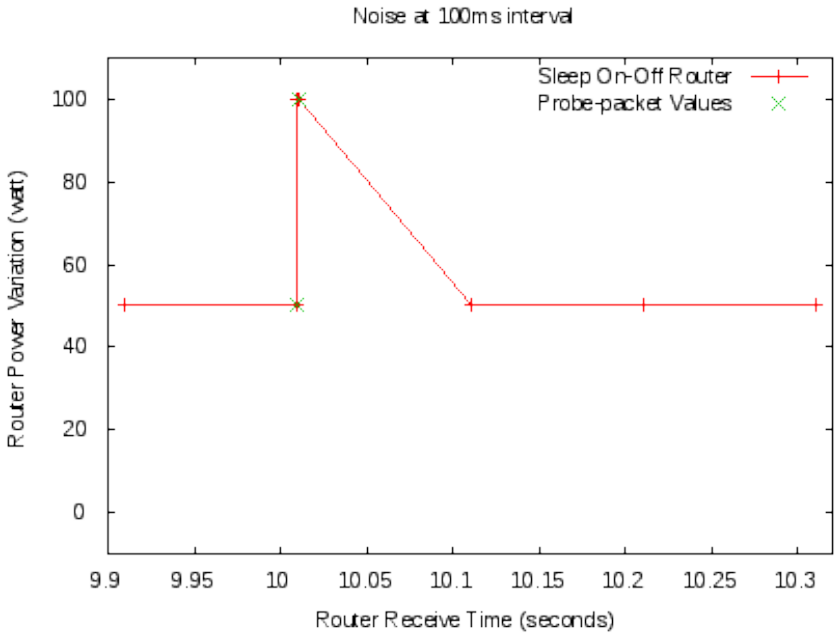


(b)

**Figure 5.7:** Router Power Variations for Linear Power Router and Sleep On-Off Router with Constant Noise Traffic at 60ms Interval.

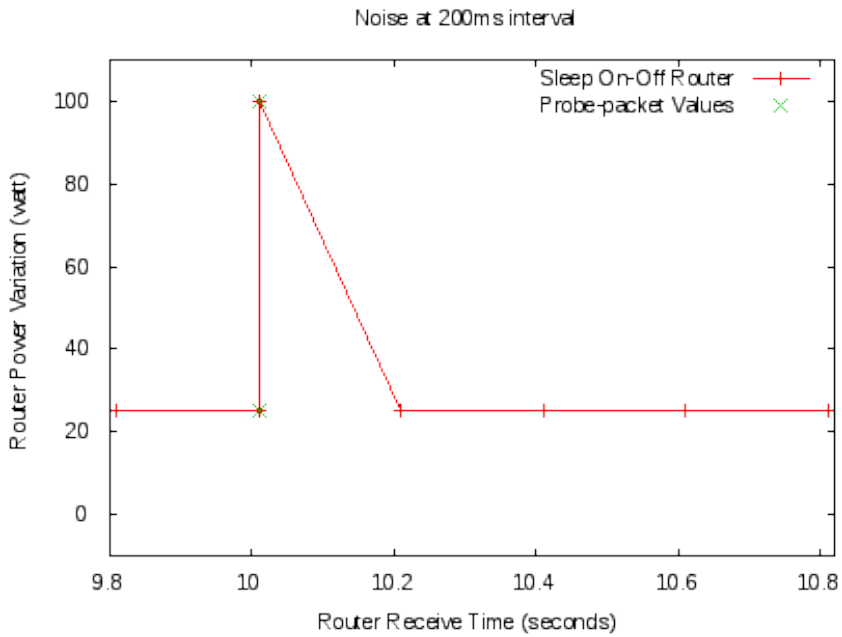
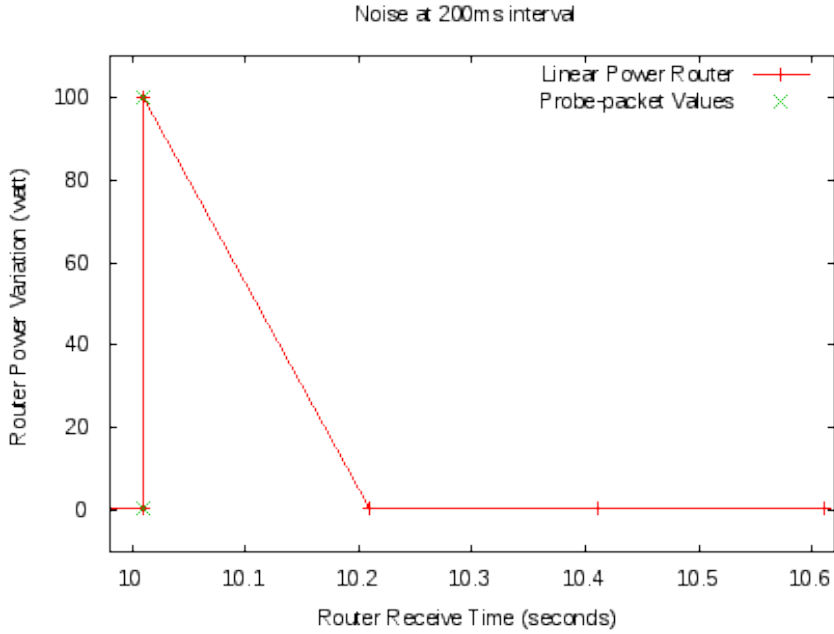


(a)



(b)

**Figure 5.8:** Router Power Variations for Linear Power Router and Sleep On-Off Router with Constant Noise Traffic at 100ms Interval.



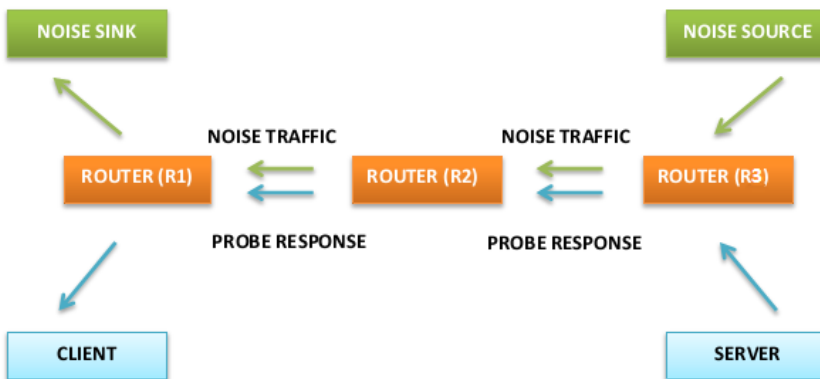
**Figure 5.9:** Router Power Variations for Linear Power Router and Sleep On-Off Router with Constant Noise Traffic at 200ms Interval.

Table 5.1 shows the comparison of power variation for the two router types.  $P$  is the initial router power prior to the arrival of first response packet and  $P'$  is the increased router power (due to back-to-back response packets) recorded by the second response packet. This power variation due to server response packets ( $P' - P$ ) is considerably higher in case of linear power router compared to that of sleep on-off router. As noise traffic interval increases from 30ms to 200ms, the power variation gap between both router types decreases. This means that, under similar noise traffic conditions, a CDN route having more number of sleep on-off routers will result in less power consumption compared to a route with more linear power routers.

Noise Interval (ms)	Power Variation of Linear Power Router (watts)			Power Variation of Sleep On-Off Router (watts)		
	P	P'	P'-P	P	P'	P'-P
30	2.7307	100	<b>97.269</b>	100	100	<b>0</b>
60	1.3653	100	<b>98.635</b>	83.33	100	<b>16.67</b>
100	0.8192	100	<b>99.181</b>	50	100	<b>50</b>
200	0.4096	100	<b>99.591</b>	25	100	<b>75</b>

**Table 5.1:** Comparison of Router Power Variations at Different Noise Levels for Single Energy-wise Router Topology.

### 5.2.3 Simulation Scenario 2



**Figure 5.10:** Simulation Scenario: Topology with Multiple Energy-wise Routers.

In this scenario, a CDN topology has been selected as shown in Figure 5.10. The topology consists of a client-server pair, a noise source-sink pair and three routers. All the routers are modeled to be energy-efficient and capable of updating energy counter values in incoming packets. This scenario is simulated in order to prove that the results obtained from previous scenario of single router topology can be extended to a multiple router network route. The simulation process remains the same as in previous scenario.

### 5.2.4 Observations

Results are presented in Table 5.2. In this scenario, it is observed that sleep router has considerably less power variation due to client-server communication compared to linear power router under similar noise traffic conditions. This observation is similar to what was concluded previously for a single router topology. In this case, the power variations from all three routers are added up in the packets.

Noise Interval	Power Variation of Linear Power Router (watts)						
	R1	R2	R3	R1'	R2'	R3'	$\sum_{i=1}^3 (R'_i - R_i)$
30 ms	2.731	16.228	2.731	16.075	100	100	<b>194.386</b>
60 ms	1.365	16.228	1.365	16.075	100	100	<b>197.116</b>
100 ms	0.819	0.863	0.819	16.228	100	100	<b>213.574</b>
200 ms	0.409	0.420	0.409	16.228	100	100	<b>214.836</b>
	Power Variation of Sleep On-Off Router (watts)						
	R1	R2	R3	R1'	R2'	R3'	$\sum_{i=1}^3 (R'_i - R_i)$
30 ms	100	100	100	100	100	100	<b>0</b>
60 ms	83.333	100	83.333	100	100	100	<b>33.333</b>
100 ms	50	52.658	50	100	100	100	<b>147.342</b>
200 ms	25	25.647	25	100	100	100	<b>224.353</b>

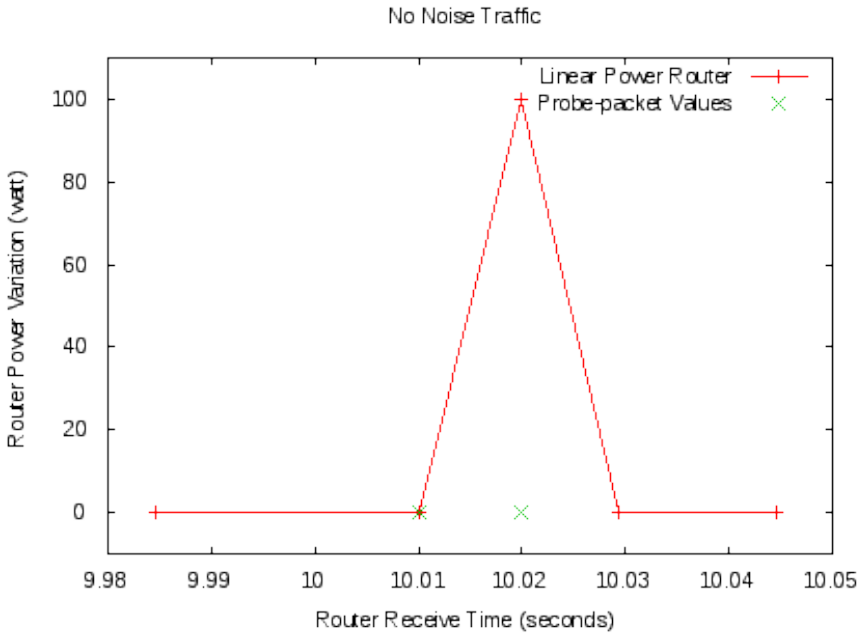
**Table 5.2:** Comparison of Router Power Variations at Different Noise Levels for Multiple Router Topology.

### 5.2.5 Analysis

The observations in Table 5.2 do not include a CDN scenario having no noise traffic. It was observed that a two packet train is not sufficient to capture the surge in router power since each packet records router power condition prior to its arrival. This

scenario is depicted in Figure 5.11. The first packet records 0 watts as the router is idle with no traffic initially. The second packet records 0.08 watts which is negligible router power due to arrival of first response packet. Even though there is a surge in router power due to arrival of second packet, it is not recorded in any of the response packets.

A similar behavior can be observed in case of linear power router R1. Referring to the results shown in Table 5.2, in case of 30ms noise traffic interval, router R1's power variation is recorded from 2.7307 watts to only 16.2282 watts whereas for the other routers, their power rise to the peak value is recorded by the second packet in the train. This is due to the difference in timing when the packets in packet train merge with the noise traffic. If packet train is sent such that one of the packets collides with a noise traffic packet, power levels surge to their peak value immediately. Therefore, in case of multiple routers, the two-packet train may not be able to accurately record power variations in some cases. Due to arrival of back-to-back packets in the packet train, router power levels reach their peak value. However, two packets may not be sufficient to record this increase in power. So, we need a third packet that would record the impact of packet train on router power. Hereafter, this model implementation will use a three packet response train.



**Figure 5.11:** Router Power Variations in the absence of Noise Traffic.

The simulations performed above support the usefulness of the energy accounting model in simple CDN topologies with regular noise traffic. The idea is to embed the values of router power variation in server response packets. A client can easily deduce information from these packets to select an energy-efficient server alternative in a simple CDN topology. This approach solves some of the challenges of implementing the energy model. However, it still needs to be tested with real-time traffic scenarios and bigger CDN topologies.

### 5.3 Energy Accounting Protocol v2.1

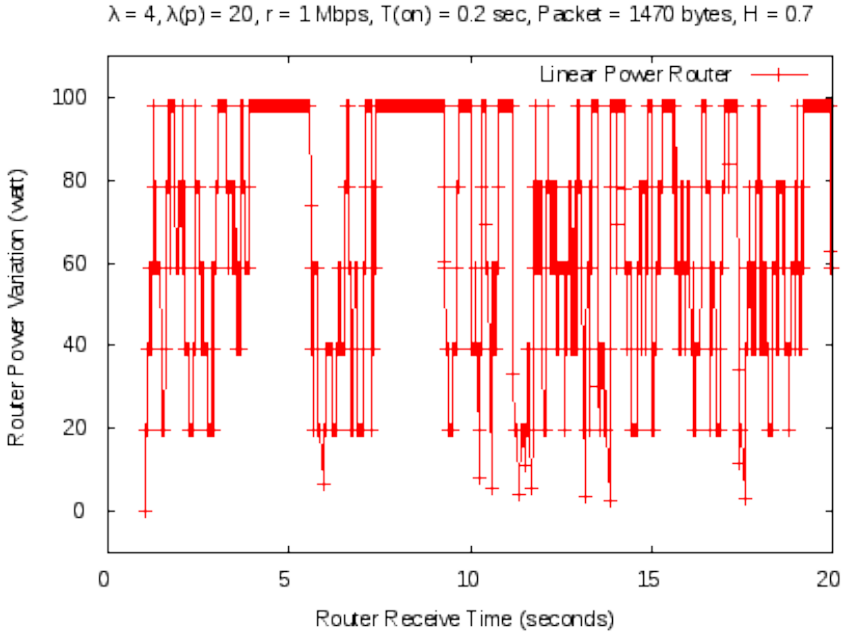
Previously, the simulations were carried out in the presence of constant noise traffic in the CDN apart from client-server communication. The power variations observed in network devices were only due to probe responses from a server and it was relatively simple to compute the network energy consumption due to newly initiated client-server communication. However, in reality, network power consumption may fluctuate due to varying traffic loads in the network. A CDN is capable of processing content requests from multiple clients simultaneously. The number of active clients may vary from time-to-time, thereby, varying the traffic levels in a CDN. As a result, power variations observed in network devices can be due to varying network load apart from the newly initiated client-server communication. It becomes rather challenging to obtain accurate information from the energy model in such network scenarios. Therefore, it is important to test the energy model in such real-time scenarios. The simulations presented in this section are performed by introducing random noise traffic in the CDN topologies apart from client-server communication.

This version of protocol is an extension of the previous two-packet response train approach. However, as concluded before, the server response should consist of atleast three packets instead of two in order to efficiently capture router power variations. In the following simulations, the model will be tested for real-time network traffic using suitable traffic generation tools available for NS3 simulator.

#### *Poisson Pareto Burst Process Model*

Zukerman et al. [ZNA03] suggests Poisson Pareto Burst Process (PPBP) as a suitable model for representing real-time traffic in packet-switched networks. Ammar et al. [ABGL11] describes a tool for generating realistic internet traffic in NS3 based on the PPBP model. In order to test the energy model with random traffic, the PPBP model is used in the simulations. The impact of PPBP traffic on a linear power router is shown in Figure 5.12. By observing the randomness in router power, it can be deduced that a one-time probe response from a server will not be able to capture the randomness of the traffic. It is challenging to calculate the impact of newly initiated client-server communication in the presence of such traffic variations.

Therefore, the protocol is modified such that a client performs probing at regular intervals for a period of time, to correctly estimate network power variations.



**Figure 5.12:** Impact of PPBP Traffic on Network Power Consumption.

### 5.3.1 Simulation Scenario

In this simulation, the single energy-wise router topology shown in Figure 5.5 is used. The difference in this case is that, instead of constant noise traffic between the noise source-sink pair, random PPBP traffic is introduced in the network. Our aim is to compare the power variations obtained by repeated probing with actual power variations in case of content delivery between a client-server pair. The simulations are carried out for a linear router as its power is highly responsive to varying traffic compared to a sleep on-off router whose power remains constant in case of heavy traffic loads. The simulation process is divided in three steps as follows:

**Step 1:** Average router power (denoted by  $P_{initial}$ ) is calculated for a given time period in the presence of only PPBP traffic.

**Step 2:** Average router power (denoted by  $P_{final}$ ) is re-calculated for the same time period with a bulk data transfer over a Transmission Control Protocol (TCP)



connection between the client and the server in the presence of PPBP traffic.

**Step 3:** As a next step, repeated probing is performed at regular intervals between the client and server over the same time period. This is done in the presence of PPBP traffic. If  $\Delta P_{probe_i}$  is the power variation calculated from the  $i^{\text{th}}$  probe response, then an average network power variation (denoted by  $\Delta P_{probe}$ ) can be calculated for the given time period from Equation 5.3.

$$\Delta P_{probe} = \left( \sum_{i=1}^n \Delta P_{probe_i} \right) / n \quad (5.3)$$

$$\Delta P_{actual} = P_{final} - P_{initial} \quad (5.4)$$

The difference between the values obtained in Step 1 and Step 2 gives the actual network power variation (denoted by  $\Delta P_{actual}$ ) due to newly initiated data transfer between client and server. This is shown in Equation 5.4. The aim is to accurately estimate  $\Delta P_{probe}$  such that its value is close to the actual network power variations ( $\Delta P_{actual}$ ). This will help the client in estimating  $\Delta P_{actual}$  without actually receiving content from the server. After obtaining  $\Delta P_{probe}$  for all server alternatives in the CDN, the client can then choose a server that has the least  $\Delta P_{probe}$  value i.e. the server is currently the most energy-efficient for delivering content to the client.

### 5.3.2 Observations

This section presents the results of simulations for different PPBP traffic samples.

#### *PPBP Traffic Scenario 1*

In this case, the PPBP traffic between noise source and sink consumes an average router power of 30.9 watts ( $P_{initial}$ ) for a time period of 20 seconds. The power variations are shown in Figure 5.13. When bulk data transfer is initiated between the client and the server in the presence of this PPBP traffic, router R1 is almost fully utilized with an average power consumption of 99.8 watts ( $P_{final}$ ), as shown in Figure 5.14. Now, the value of  $\Delta P_{actual}$  can be calculated from Equation 5.4.

In the next step of simulation, probe response packets are sent from server to client at regular intervals in the presence of sample PPBP traffic. Probe packets are able to accurately capture router power variations as shown in Figure 5.15. The value of  $\Delta P_{probe}$  is obtained from frequent probing and compared with the expected value,  $\Delta P_{actual}$ . The results are presented in Table 5.3. An error of 9.4 watts is found on comparing the probing outcome with expected power variations for a probe interval of 0.5 seconds and duration of 20 seconds.

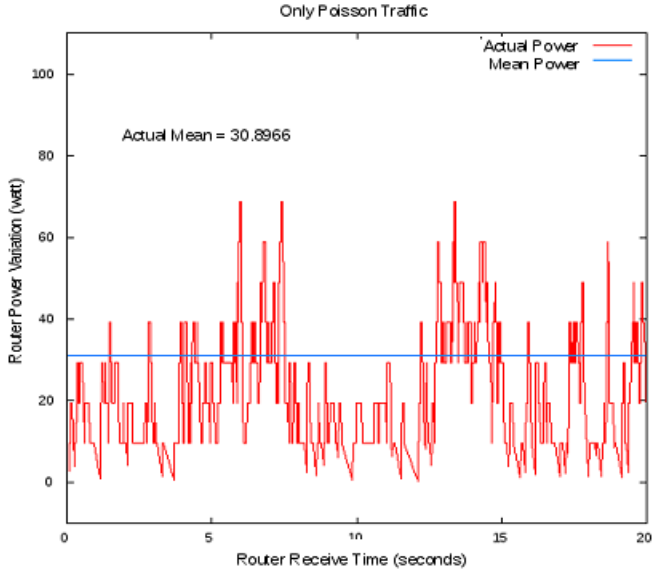


Figure 5.13: Scenario 1: Power Variation of a Router due to PPBP Traffic.

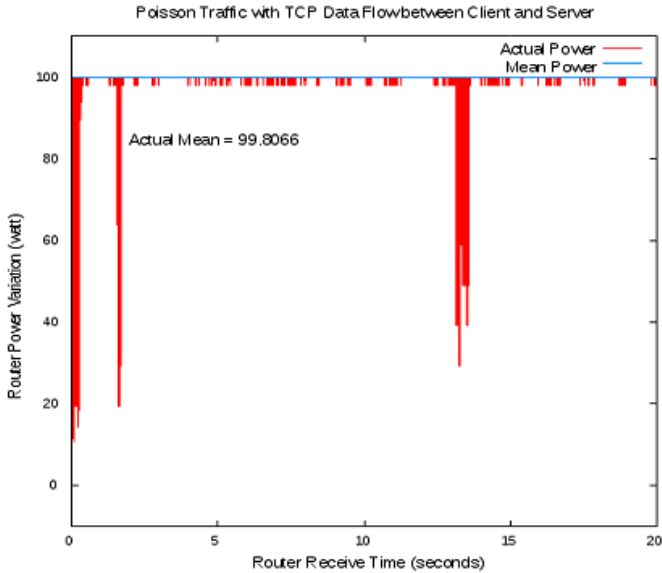
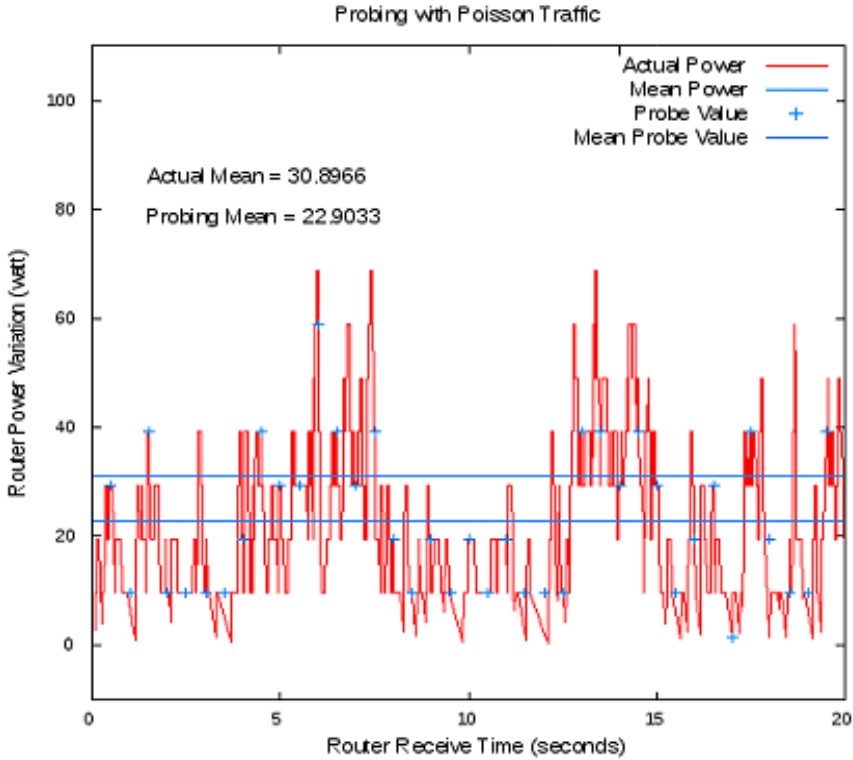


Figure 5.14: Scenario 1: Power Variation of a Router due to PPBP Traffic with TCP Data Flow between Client and Server.



**Figure 5.15:** Scenario 1: Router Power Variations due to PPBP Traffic captured by Probe Packets.

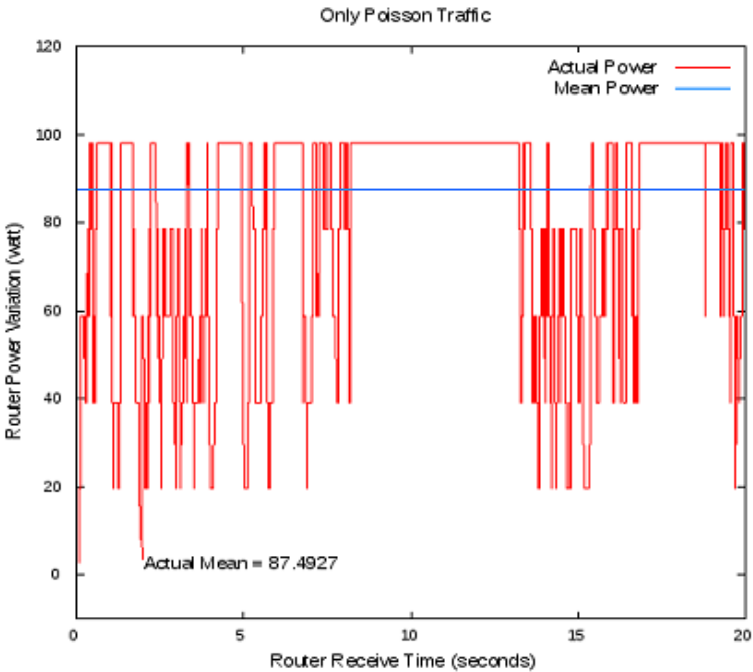
<b>Time Window (sec)</b>	20	
$P_{initial}$ (watts)	30.897	
$P_{final}$ (watts)	99.807	
$\Delta P_{actual}$ (watts)	68.91	
<b>Probe Interval</b>	$\Delta P_{probe}$ (watts)	<b>Error (watts)</b>
0.5 sec	78.334	<b>9.424</b>
1 sec	78.233	<b>9.323</b>
5 sec	78.318	<b>9.408</b>

**Table 5.3:** Scenario 1: Comparison of Probing Outcome with Actual Router Power Variations.

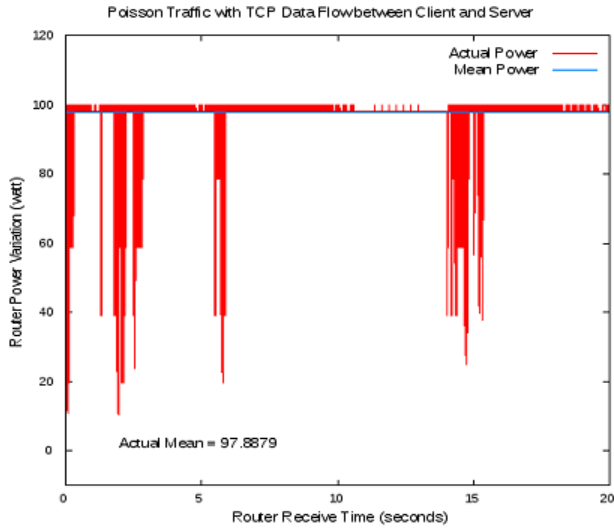
### *PPBP Traffic Scenario 2*

This case is similar to the previous case but with a different PPBP traffic sample. In this case, the sample PPBP traffic between noise source and sink consumes an average router power of 87.49 watts ( $P_{initial}$ ) for a time period of 20 seconds. Router power variations are shown in Figure 5.16. When a bulk data transfer is initiated between the client and the server in the presence of this PPBP traffic, router R1 consumes an average power of 97.89 watts ( $P_{final}$ ), as shown in Figure 5.17. The value of  $\Delta P_{actual}$  can be calculated as before.

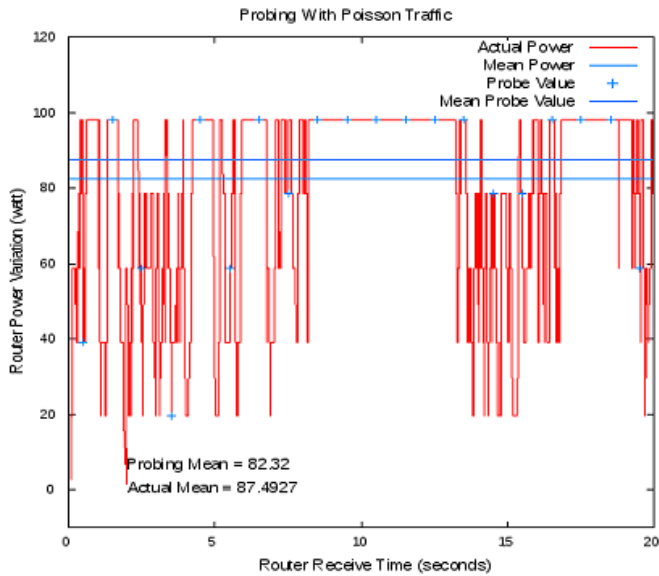
As the next step of simulation, probe response packets are sent from server to client at regular intervals in the presence of sample PPBP traffic. Router power variations captured by probe packets are shown in Figure 5.18. The results are presented in Table 5.4. An error of 4.6 watts was found on comparing the probing outcome with expected power variations for a probe interval of 0.5 seconds and duration of 20 seconds.



**Figure 5.16:** Scenario 2: Power Variation of a Router due to PPBP Traffic.



**Figure 5.17:** Scenario 2: Power Variation of a Router due to PPBP Traffic with TCP Data Flow between Client and Server.



**Figure 5.18:** Scenario 2: Router Power Variations due to PPBP Traffic captured by Probe Packets.

<b>Time Window (sec)</b>	20	
$P_{initial}$ (watts)	87.49	
$P_{final}$ (watts)	97.89	
$\Delta P_{actual}$ (watts)	10.40	
<b>Probe Interval</b>		
	$\Delta P_{probe}$ (watts)	<b>Error (watts)</b>
0.5 sec	15.025	<b>4.625</b>
1 sec	15.124	<b>4.724</b>
5 sec	20.04	<b>9.64</b>

**Table 5.4:** Scenario 2: Comparison of Probing Outcome with Actual Router Power Variations.

### 5.3.3 Analysis

The simulations performed using PPBP traffic samples support the usefulness of the energy accounting model in simple CDN topologies with real-time traffic. Two different PPBP traffic samples were used to perform the simulations. Results are depicted in Tables 5.3 and 5.4 for PPBP traffic scenarios 1 and 2 respectively. Accuracy of the results depends on the following factors.

#### *Randomness of network traffic*

Both the cases involved highly random PPBP traffic samples. An error as low as 4.6 watts was obtained for one of the cases. However, in case of less random traffic, the energy model can provide a much higher accuracy level. It is not in the scope of this thesis work to study traffic patterns in CDNs. The frequency of probing can be adjusted depending on the randomness of CDN traffic. More random the network traffic, more frequent is the probing requirement.

#### *Probing Frequency*

Frequent probing helps in predicting router power variations which may occur due to content transfer between a client and server. More frequent probing results in more accurate router power estimation.

#### *Selection of Time Window*

The above simulations were performed for a time window of 20 seconds. The duration is directly proportional to traffic randomness and accuracy of results. It

can be longer in order to have more accurate predictions about the CDN traffic.

Apart from the above factors, it is also important that the probe response should consist of appropriate number of packets. Previously, it was observed that a two-packet response is not suitable to correctly record power variations in all scenarios of noise traffic. However, a three-packet long response was found to be sufficient to capture router power variations.

Using the protocol, clients in a CDN can successfully deduce power variations for different server alternatives in any kind of network traffic scenario. They can then select the server that is found to be most energy-efficient to deliver content to the client.





# Chapter 6

## Discussion

This chapter analyzes the energy accounting model focusing on the main challenges in implementing the model. It also presents an overview of the impact of network dynamics on the model. Later, the chapter discusses the idea of integrating the model with existing network performance metrics such as network throughput.

### 6.1 Analysis of the Energy Accounting Model

This thesis work designs and implements a packet-level energy accounting model using NS-3 simulator. Chapter 5 presents an energy accounting protocol that uses the energy model for the use case of selecting energy-efficient CDN servers to deliver content to end users with minimum power consumption. The protocol has been reformed during the course of simulations to provide better power estimates. An analysis of the various versions of protocol is presented in Table 6.1. Using the energy accounting protocol v2.1, it is possible to obtain power estimations which can help the clients in distinguishing between various server alternatives available for content delivery.

Protocol	Version 1.0	Version 2.0	Version 2.1
No. of packets in probe response	1000	2	3
Values embedded in response packets	Each packet contains $\Delta E_t$ (amount of energy consumed by routers on a route to process the packet) and $Hops$ (number of hops traversed by the packet).	Each packet stores amount of energy consumed by routers on the path from server to client prior to the arrival of the packet.	Each packet stores amount of energy consumed by routers on the path from server to client prior to the arrival of the packet.
Observations	<p><b>Constant power router:</b>  <math>\Delta E_t = 0</math></p> <p><b>Linear power router:</b> <math>\Delta E_t = k * S/\mu</math></p> <p><b>Sleep On-Off router:</b> <math>\Delta E_t \propto 1/\lambda_t</math></p>	<p>By sending probe packets back-to-back, it is found that sleep routers have considerably less power variations compared to linear power routers under similar noise traffic.</p>	<p><math>\Delta P_{probe}</math> is calculated by sending probe packets back-to-back. It is found to be considerably accurate even in cases of random noise traffic in the network.</p>
Limitations	<p>Firstly, <math>\Delta E_t</math> can be negative in cases of irregular network traffic and cannot be always used to compare network routes in those cases. Secondly, having a packet train of 1000 packets is an overhead to the network. Fewer packets can be used in the response.</p>	<p>A 2-packet train is not sufficient to capture power variations in case there is no noise traffic in the network. Even if noise traffic is present, the protocol may still be incapable of capturing correct power variations in networks for some traffic scenarios.</p>	<p>Probing needs to be repeatedly performed in case of random noise traffic. Accuracy of results depends on traffic randomness, probing frequency &amp; selection of time windows for probing. The protocol is not immune to the problems created by routing instability and other network dynamics.</p>

**Table 6.1:** Analysis of the Energy Accounting Protocol.

Apart from CDNs, the energy model can also be applied to several other use cases for promoting green networking. Some of the use cases have been discussed briefly in section 3.2. A three-packet response train can be used in those cases to capture information related to network power consumption. As mentioned earlier, the energy model can be extended to other network devices such as hubs, switches, gateways and can also be implemented in other layers of network stack apart from the IP layer. The energy accounting scheme is very versatile as it can be implemented for any ICT component between a packet source and destination. Application level energy accounting could also be a possible extension to the model.

### 6.1.1 Implementation Challenges

In order to analyze the energy accounting model, there can be several different scenarios in CDNs. For example, the model can be tested for different types of router behaviors, various topology sizes or different kinds of network traffic. The main challenge is to breakdown these scenarios into possible test cases for assessing the performance of the model along with keeping the complexity of simulations under control.

Our approach has been to proceed from simplest CDN topologies consisting of two-hop network routes to longer network routes. One major concern has been to minimize the impact of routing algorithms to simplify the analysis of simulation outcomes. Since, our implementation does not use customized routing protocols, it is important to define topologies having a single network route between the client and server for the purpose of simplifying the analyzes of simulation outcomes. Our step-by-step approach to implement the model in NS-3 has been very significant in providing a direction to our research.

## 6.2 Impact of Network Dynamics on the Model

Network dynamics can pose a great challenge to the energy model. There is a concern about route instability in networks. Internet has evolved and become extremely complex in recent years. Several efforts are being made to study and quantify the diversity, stability and symmetry of internet routes [SSW10, LIJM<sup>+</sup>10]. Routing instability can be defined as "*Rapid change of network reachability and topology information*" [LIJM<sup>+</sup>10]. It is caused due to hardware failures or software errors in the network or due to deliberate attacks on the network. The introduction of complex load balancing and traffic engineering schemes in the internet has made it even harder to analyze the stability of internet routes.

The solution to this problem is repeated probing. Once a client finds an energy-efficient server for content delivery, it initiates the process of receiving content from

the server. However, network metrics change dynamically. During the course of content delivery, selected path may become less energy-efficient. We need a scheme that dynamically changes the server as soon as a more energy-efficient server is available. The probing needs to be performed repetitively in case the performance of current server degrades after some time. However, it can be difficult to predict how frequently the probing should be performed.

### 6.3 Model Extension

Through the energy accounting model, we are trying to promote energy efficiency in networks. However, the proposed probing scheme neglects routing and other network traffic engineering factors. If the model is used in networks to promote energy efficiency, the performance and QoS of the networks may be compromised. As an example, consider a case of two network routes. Assume that in case of first route, most of the routers are fully-utilized i.e. they are operating at the maximum power level. A probe response through this route will result in very little increase in the network power consumption since the devices on this route are already operating at peak load. However, the route will offer a lower throughput due to higher traffic. In case of second route, assume that most of the devices are under-utilized i.e. they are operating at lower power levels. Probe response through the second route will result in a higher power variation in the network and the route will be less energy-efficient compared to first route. However, the second route will offer a better throughput due to less traffic on the route. It is very common to find such scenarios in networks. With respect to energy efficiency, the first route should be preferred whereas with respect to network throughput, the second route should be preferred.

After carefully considering several network traffic engineering factors, it can be concluded that the model should also take into consideration network throughput along with network energy consumption to suggest optimal routes for packets through a network. There should be a balance between throughput and energy efficiency. One should not be compromised in order to give preference to the other. However, the preferences may vary depending upon the use case and application requirements where the model is implemented. In the above example, route selection should be done such that the ratio of network power variation to network throughput ( $\Delta P/T$ ) should be less for the route. First route should be preferred to the second route if the following equation holds.

$$\Delta P_1/T_1 < \Delta P_2/T_2 \tag{6.1}$$

There can be several scenarios in networks which may be similar to the above example. In such scenarios, the energy accounting model should be able to merge with existing network traffic engineering schemes. In context of CDNs, the model

should consider both energy efficiency as well as network throughput in order to perform server selection for requesting content delivery. Users will not prefer energy-efficiency if it compromises with the QoS offered to them. In the energy accounting protocol discussed in section 5.3, server sends three probe packets back-to-back. If a network route is congested, the client will receive these packets with a certain time gap between each packet depending on the amount of congestion. This can be used to calculate throughput ( $T$ ) offered by the route. Power variations ( $\Delta P$ ) can be calculated in the same way using the energy model. Clients can easily obtain a ratio of  $\Delta P/T$  for various server alternatives in the CDN. Based on the obtained values, clients can choose the server offering the lowest  $\Delta P/T$  value i.e. more throughput and less power consumption.



# Chapter 7

## Conclusion and Future Work

Green ICT (Information and Communication Technology) aims at reducing the environmental impacts of ICT operations, maximizing energy efficiency and promoting recyclability. Networks play a crucial role in the green ICT initiatives. With the increase in demand of internet usage, there is an increase in the overall network power consumption contributing to higher carbon emissions in the ICT sector. Therefore, network devices and infrastructure, which make up a considerable share of ICT power consumption, should be made more energy-efficient.

This master thesis designs and implements a packet-level energy accounting model that allows measuring the energy consumption in networks to optimize their usage. It was highly challenging to predict the usability of such a model prior to the findings of this work. The main idea is to collect energy-related information in IP packet headers. The information can be related to the energy consumed by a packet at each hop while traversing a network. This information is later processed to assess various characteristics of network energy consumption.

The energy-accounting model can be applied to several use cases such as aid in network traffic engineering and providing energy incentives to ISPs. The thesis analyzes the application of this model to the use case of selecting energy-efficient servers in CDNs. When a client requests content from a CDN, several mirror servers in the CDN are capable of delivering content to the client. In normal circumstances, a server that is geographically closest to the client is assigned to respond to the client's request. Energy-efficiency is not a priority in the functioning of CDNs.

In this thesis, instead of assigning CDN servers to clients on the basis of geographical location or QoS, we try to assign a server based on the amount of energy consumed in the network to process a client request. The process involves the client sending probe requests to possible server alternatives in the CDN. Each server responds with a probe response which consists of a packet train. The packets in the probe response capture information about power consumption in the network

which may occur due to content delivery between the client and the respective server. When a client has received probe responses from all the server alternatives, it then selects the server that will result in least power consumption to deliver content to the client.

The energy model is implemented using the NS-3 simulator. It is tested for the above use case using various network topologies and traffic scenarios. The aim is to predict the increase in power consumed by a network due to newly initiated client-server communication. From the simulations, it is found that the probing mechanism successfully predicts power variations in a network in the presence of constant noise traffic. However, there is a need of repeated probing to correctly estimate power variations in the presence of highly random noise traffic in the network. It is important that there are appropriate numbers of packets in a probe response and the packets are sent back-to-back.

Simulations also support the fact that a sleep on-off router is more energy-efficient compared to a liner power router. The power estimations obtained from the energy model are found to be highly accurate for selected simulation scenarios. The accuracy levels vary depending upon the randomness of network traffic, probing frequency, duration of probing and complexity of network topology. The mechanism designed to estimate the amount of power consumed is also affected by network dynamics. Probing frequency may need to be adjusted depending on the amount of route instability in a network.

Through the model, clients are able to predict power variations in CDNs which may occur as a result of content delivery between those clients and a CDN server. The power estimates can be used to select the most energy-efficient CDN server alternative for delivering content to a client. The thesis work proves that there is a scope of using packet-level energy accounting mechanisms for promoting energy efficiency in networks. End users can be made aware of their carbon footprint and are able to contribute to green networking.

Additionally, there is also a possibility to integrate the model with other network performance metrics such as network throughput in order to increase its usability and obtain a balance between QoS and energy-efficiency. There should be a possibility to apply the model as an enhancement to existing networks. It is important for the model to be adaptive to the energy-saving requirements and preferences which may vary depending upon the use case where it is applied. The energy-accounting model implemented in this thesis has the capability to promoting energy-efficiency in networks without compromising network performance and QoS.

As a part of the future work, the model needs to be tested for bigger network topologies. There is a possibility to use *Rocketfuel* topologies [SMW02] for simulations



in NS-3. Apart from that, there are some limitations of the model such as its reaction to network dynamics. These issues can be addressed as a part of the future work. Some efforts are also required to integrate the model with network throughput as discussed above. Later on, the possibilities of applying the model to other uses cases can also be explored.



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