國立臺灣大學電機資訊學院資訊工程學系

碩士論文

Graduate Institute of Computer Science and Information Engineering

College of Electrical Engineering and Computer Science

National Taiwan University

Master Thesis

網路路由器節能演算法之研究

A Study on Energy Conservation Algorithm for Internet Router

蔡明峰

Ming-Feng Cai

指導教授：林風 博士

Advisor: Phone Lin, Ph.D.

中華民國一百零一年七月

July, 2012

Acknowledgement

兩年的碩士生涯轉眼間就過去了，又到了畢業的時候。首先我要感謝我的指導老師，林風教授。在兩年的碩士生涯中，林風老師扮演著亦師亦友的角色，讓我學到做研究的熱情以及態度，並且順利完成了這篇論文。 接著要特別感謝懷磊學長，在整個研究過程中，讓我學習到許多做研究的觀念與方法，學長也在平日也親立親爲，讓我體會到全力以赴的研究態度。同時，我也非常感謝林一平教授、Dr.Charlie Tai、以及顏在賢博士擔任學生的口試委員，並且對本篇論文提供許多良好的建議，使得這篇論文更加完整。

接著我要感謝與我在這兩年一起奮鬥的實驗室同仁們。啓維學長、家朋學長、有倫學長、亭佑學姊、厚鈞學長、思適學長、家綸學長、 宗哲學長、坤豐、冠銘、振翔、百俊、彥婷、恩豪，與你們相處的點滴永難忘懷，在你們的陪伴下，讓我十分快樂的度過這段研究的時光。

最後我要感謝我的家人，我的父母與弟弟，在這兩年中給我全力的支持與鼓勵，讓我可以全心全意的認眞讀書，順利地拿到碩士學位。

Chinese Abstract

在即將來臨的M2M或是物聯網的世界，機器在特定時間內所產生大量的資料可能對網際網路造成相當大的負擔。 爲了確保大範圍的M2M通訊正常運作，佈置網際網路路由器是必要的。這些網際網路路由器會造成相當大的能源消耗， 但是這些路由器在大部分的時間都是閒置的。 爲了替這些大量的路由器節省能源，在這篇論文中我們提出分析模組去分析大量的M2M資料流量對路由器之影響。 我們提出了路由器節能機制去對網際網路路由器做節能，並且利用模擬來探討此機制的效能。

關鍵字(Keywords): 節約能源(Energy Conservation)、網際網路路由器(Internet Router)、M2M通訊(Machine to Machine Communications)

English Abstract

In the coming Machine to Machine (M2M) or Internet of Things (IoT) world, bursty data from millions to trillions of machines may cause significant traffic in the existing Internet during certain time periods. To ensure such large-scale M2M communications, deployment of more Internet routers is required, thus increasing the energy consumption of Internet routers. However for most of the time, the routers are idle. To save energy for large numbers of routers, in this paper, we propose analytical models to analyze the effects of M2M traffic on router behavior. We then propose a Power Saving for Routers (PSR) mechanism that saves energy for Internet routers. Simulation experiments are conducted to investigate the performance of the proposed algorithm.

Keywords: Energy Conservation; Internet Router; Machine to Machine Communications;

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In the coming Machine to Machine (M2M) or Internet of Things (IoT) world, bursty data from millions to trillions of machines may cause significant traffic in the existing Internet during certain time periods. To ensure such large-scale M2M communications, deployment of more Internet routers is required, thus increasing the energy consumption of Internet. The Internet energy conservation issue will be a big challenge for the coming M2M communications.

Several reports show that Information and communication technology (ICT) consumes a large amount of electricity and produces a great amount of CO_2. According to the research [13], the CO_2 generated by the worldwide ICT is approximately 2% of global manmade CO_2 each year. Also, as reported in [3], the electricity consumed by ICT (without consumer electronics) is about 4.3% and 8% of the overall electricity consumption in European Union (EU-27) and the US, respectively. Along with the rapid growth of the Internet usage and data rates in the coming M2M world, the energy consumption

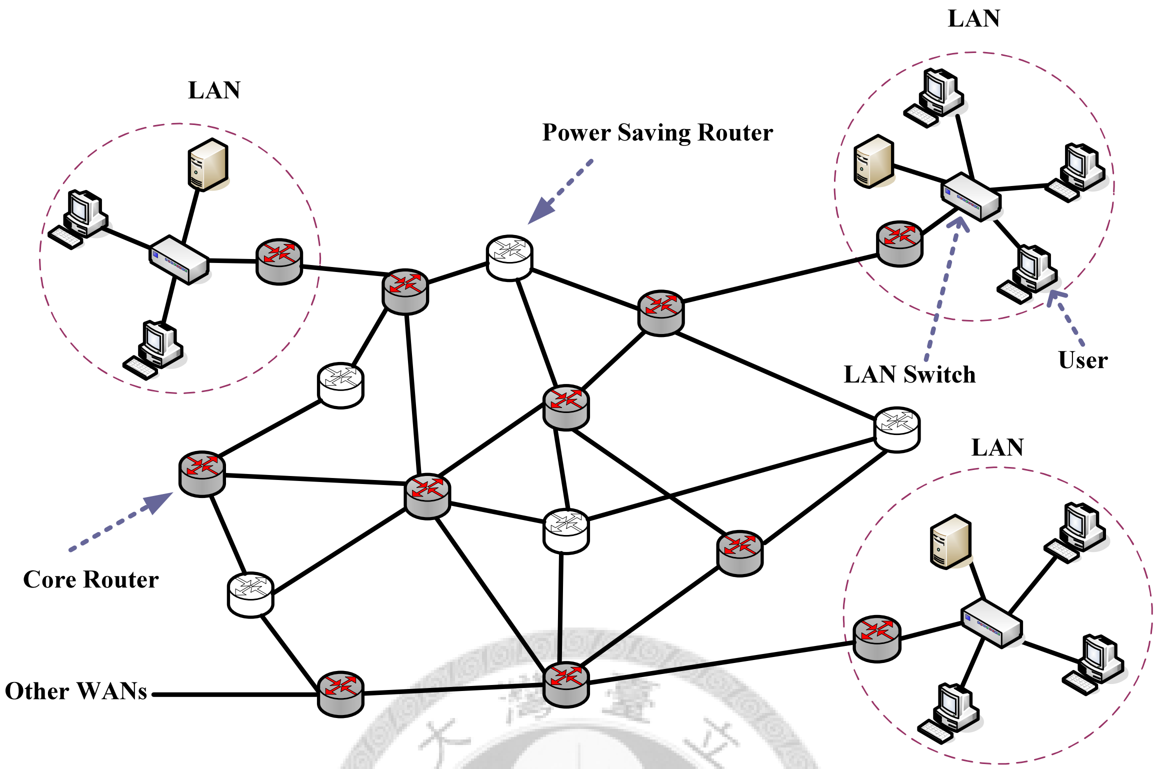


Figure 1.1: The Internet architecture

will keep growing.

Figure 1.1 illustrates the existing general Internet architecture that will also offer transmission service for M2M. The core of the Internet consists of routers and switches. Routers are used to provide direct communications between Local Area Networks (LANs), and mainly in charge of processing packets which are sent through WAN to the proper LAN based on the routing information in the packet header. When the packets reach the LAN, the switches are responsible to route the packets to the correct machine. Both switches and routers play major parts in Internet. Basically, routers and switches share the same architecture and functionalities. Most of power consumption is caused from routers and switches in Internet. In this paper, we focus on reducing power consumption of routers and thereby reduce the overall Internet power consumption.

Energy conservation for Internet has been noticed in the previous works. Chiaraviglio et al. [8] proposed heuristic algorithms to decide how to turn off some nodes and links in order to minimize the total power consumed by the network under the constraints of connectivity and Quality of Service (QoS). The decision is based on the knowledge of the entire network topology and the total traffic demand, which requires a centralized server to maintain the knowledge and incurs extra signaling overhead to the network to collect the knowledge. It costs a lot to deploy the algorithms in the existing Internet, which is considered impractical. Centralized algorithms are also proposed in the previous works [1][7]. In [1], the authors proposed a three-phases centralized algorithm. The links to be off are selected based on the network topology by a centralized node. In [7], the authors considered a real IP backbone network and the corresponding traffic profile to evaluate the energy cost of a router and then determine whether the router can be turned off. Similar to the work [8], deployment of the algorithms in [1][7] are costly and considered impractical in the existing Internet infrastructure.

Gupta et al. [11] proposed methods to shut down the interfaces of Ethernet LAN switches and and the hosts attached to the switches based on traffic arrivals and buffer occupancy of the switches, rather than the whole network conditions. In Gupta's methods, interfaces move into the sleep mode when they are idle (i.e., the buffer is empty or under-utilized). All packet arrivals during the sleep time period are queued in a buffer The sleep time period for the interface is determined by estimating packet inter-arrival time, where a maximum sleep period t is computed such that the probability that more than n packets arrives during t is bounded by some threshold. Gupta's methods successfully conserve power by employing the sleep mode. However, the proposed methods incur the following problems: The selection of the sleep time period is not given in this paper, and the buffer overflow may occur during the sleep time period (i.e., packets may lose). The QoS for packet delivery may degrade significantly.

In the paper, we propose a mechanism, Power Saving for Router (PSR), to save the power consumption for routers. The PSR is run in a router, i.e., the PSR is a distributed mechanism without central control. In other words, it need not maintain the whole network information in PSR. The PSR is considered practical to be deployed in the Internet. We consider the Internet consists of two kinds of routers, core router and power saving router. The core router is without implementation of PSR, meanwhile the power saving routers are implemented with the PSR mechanism. As mentioned previously, M2M traffic has the characteristic, burstness, i.e., packets from millions to trillions of machines may cause significant traffic in the existing Internet during certain time periods. In the PSR mechanism, an interface in a router can be in the active mode, the sleep mode, or the forbidden mode. In most of time, the power saving routers are in the sleep mode. When the packet traffic increases, the power saving routers move to the active mode to serve the bursty packet traffic. Besides the sleep mode and the active mode, we define the forbidden mode to prevent packet data lost during the sleep time period of a power saving router. An algorithm is proposed to adjust the sleep time period based on analysis of the power saving router's behavior. Details of the PSR mechanism will be elaborated in the next section.

The remainder of the thesis is organized as follows. In Section 2, we describe the architecture of a router. In Section 3, we illustrate the behavior of a router and propose the Power Saving for Routers (PSR) mechanism. In Section 4, we propose the analytical models to investigate the performance of the PSR mechanism. In Section 5, we develop the simulation model for the PSR mechanism. Finally, we conclude this paper in Section 6.

Chapter 2

The Architecture of A Router

In this section, we illustrate the simplified architecture of a router [6]. As shown in Figure 2.1, the major components of a router include a routing processor, a switch fabric, and one or more interfaces.

Routing Processor: The main functionalities of the routing processor (see Figure 2.1 (1)) include execution of the routing protocol (e.g., OSPF [12], RIP [5], and BGP [14]), routing table maintenance, and network management functions.

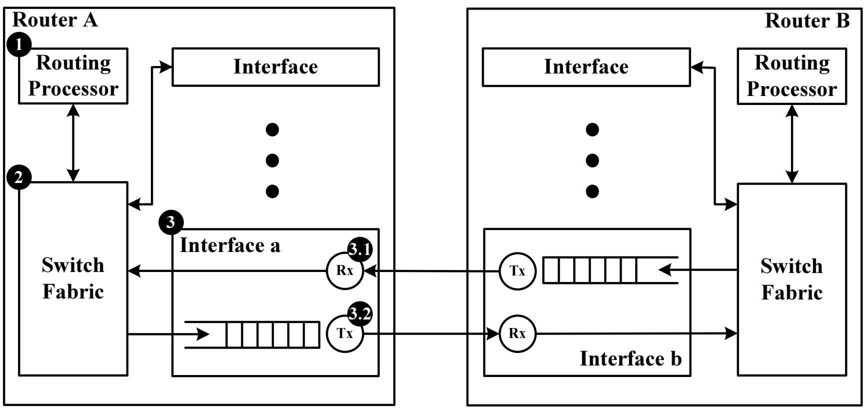


Figure 2.1: The architecture of a router

Switching Fabric: The switching fabric (see Figure 2.1 (2)) connects the input ports (Rx; Figure 2.1 (3.1)) to the corresponding output ports (Tx; Figure 2.1 (3.2)) for the routing packets among interfaces within a router.

Interface: An interface (see Figure 2.1 (3)) consists of an Rx and a Tx. The interfaces of two neighboring routers are connected through a bi-directional physical link.

- The Rx performs the following functions: (I) the physical layer functionality to terminate an incoming physical link to a router; (II) the data link layer functionality with the data link layer functionality on the other side of the incoming link; (III) a lookup and forwarding function to forward a datagram into the switching fabric and to forward control packets (i.e., packets carrying routing protocol information) to the routing processor.
- The Tx stores the datagrams forwarded from the switching fabric in a buffer, and then transmits the datagrams on the outgoing link. In other words, the Tx performs the data link and physical layer functionality with the Tx on the other side of the link. Let the buffer size of the Tx be B. Suppose that when a packet arrives at the Tx of an interface, there are m packets queued in the buffer, where $m \geq 0$. If $m = B$, this packet arrival is dropped. Otherwise (i.e., $m < B$), this packet arrival is stored in the buffer. The Tx can transmit the queued packets in FIFO order, which is an implementation issue and is not discussed in this paper.

Chapter 3

The Power Saving for Routers (PSR) Mechanism

In this section, we propose the Power Saving for Routers (PSR) mechanism for energy saving of routers. The PSR mechanism is run in the power saving router, which is a distributed control mechanism.

We maintain a state machine (see Figure 3.1) consisting of three modes, active mode, sleep mode, and forbidden mode to control the behavior of an interface. We define a sleep timer (denoted by T_s) for an interface. Consider the link between Interface a (of Router A) and Interface b (of Router B). The behavior of an interface in each mode is given below:

Active Mode: The Tx and Rx of an interface are powered on to transmit and receive data, and they behave the same as the standard Tx and Rx.

Sleep Mode: The Txs and Rxs of two interfaces between a link are turned off, and the

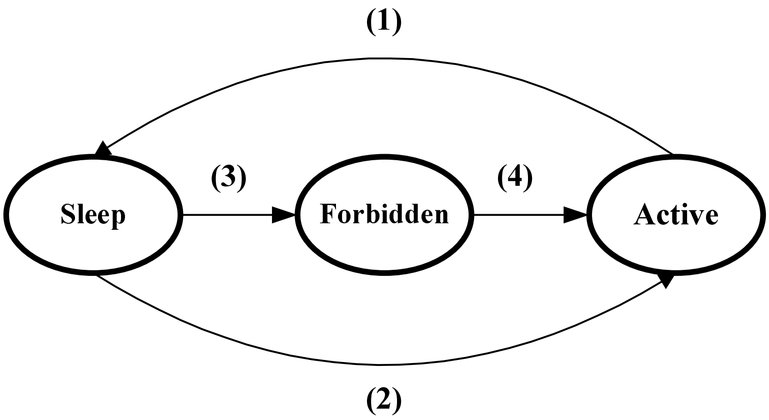


Figure 3.1: State transition for an interface

buffer of the Tx functions as well. In other words, in this mode, there is no packet exchange through a link. When a packet (to be transmitted) arrives at the Tx, it is stored in the buffer. In the sleep mode, if the number of buffered packets reaches $\lfloor \Delta B \rfloor$, the interface moves into the forbidden mode (to be elaborated later), where Δ is a threshold used to determine whether the link-off event should be reported to the router, and $0 < \Delta \leq 1$. When an interface moves into the sleep mode, the sleep timer T_s is triggered. The interface is turned on when the T_s timer expires.

Note that in this mode, the network is not award of that the link is turned off. The packets are routed according to the original routing path. However, the end-to-end transmission delay may increase. With the sleep mode, we potentially save the energy consumption for an interface without affecting the routing in the Internet.

Forbidden Mode: When the number of buffered equals to $\lfloor \Delta B \rfloor$, an interface moves from the sleep mode to the forbidden mode. In this mode, the interface functions the same as that in the sleep mode. The difference is that the buffer of an Tx is turned off, the link-off event is reported to the router, packet arrivals to the interface are forwarded to the other interfaces in the router, and the routing processor informs other routers that the link-off event. Therefore, with the forbidden mode, our mechanism can prevent the packets to be transmitted from being dropped during the time period when the Tx and Rx of an interface are turned off. In the forbidden mode, the routing in the Internet should be changed. That is, the routing path reestablishment procedure should be exercised, which can be done through for example, OSPF [12], RIP [5], and BGP [14] protocols. Extra signaling overhead is required for routing path reestablishment.

Note that as mentioned previously, our mechanism is implemented in the power saving routers. Therefore, we can pre-config two routing tables for Internet with/without the power saving routers. Therefore signaling overhead is considered minor in our mechanism. In this paper, we do not touch on the issues related to the the routing path reestablishment, which can be found in the existing standards, e.g., OSPF [12], RIP [5], and BGP [14] protocols.

The transitions in the state machine (see Figure 3.1) are elaborated as follows:

Transition (1): The transition from the active mode to the sleep mode occurs when one of the following events is detected:

Event e_1**:** There is no packets stored in the buffer of a Tx (i.e., $m = 0$), and the Tx is idle. When this event is detected, the sleep timer T_s for the interface is triggered, the Rx and Tx of the interface are turned off, the sleep-start message (carrying the time length of the sleep timer T_s) is sent to the other router of the link. The Rx of Tx of the other interface are moved into the sleep mode.

Event e_2**:** A sleep-start message is received by an interface.

Transition (2): The transition from the sleep mode to the active mode occurs only when the sleep timer T_s expires.

Transition (3): This transition from the sleep mode to the forbidden mode occurs when one of the following two events is detected:

Event e_3**:** $m > \lfloor \Delta B \rfloor$. When this event is detected, the interface reports he link-off event to the neigherbpring router and the interface on the other side of the link.

Event e_4**:** The interface receives a link-off event.

Transition (4): The T_s timer expires. The router informs its neighboring routers the link-on event.

Note that in the PSR mechanism, the setup of the sleep timer T_s may affect the performance of the router significantly. A longer T_s implies that the interface sleep longer (i.e., more power are potentially saved), and it is more likely that the interface moves into the forbidden mode, and extra signaling is required for routing path re-establishment. However, if we set T_s shorter, the interface is more likely to switch between on and off with more power consumption. In the next we propose analytical models to study how to set up the sleep timer.

Chapter 4

Analytical Models

In this section, we propose analytical models to study the three issues: First, we study how the power saving ratio is affected by the setup of the sleep time in Section 4.1. Second, we study how to set up the sleep timer based on the delay time in Section 4.2. Following by that, we study the switch-on overhead for the sleep period in Section 4.3.

4.1 Effects of T_s on Power Saving Ratio

In this section, to derive the power saving ratio for an interface, we utilize the M/G/1 model with an exhaustive service and multiple vacation (E, MV) policy [16], denoted by "M/G/1 (E, MV)". A sleep period is considered as a vacation in the M/G/1 (E, MV) model. An interface keeps on handling packets until the interface is idle (i.e., there is no packet in service and waiting in the buffer), and then takes vacations (switching to the sleep mode) as long as the interface is idle, implying that there is no idle period for the

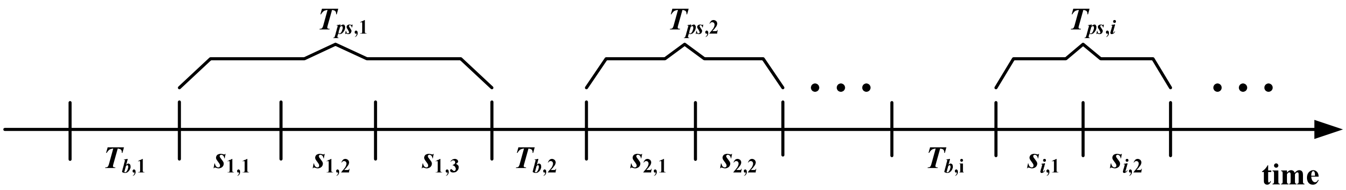


Figure 4.1: Timing diagram for busy and power saving periods

interface. The interface returns to the active mode when there are packets waiting in the buffer at the end of each sleep period. For the sake of simplicity, we assume the buffer size is infinity, i.e., the interface is never moved to the forbidden mode.

Consider Interface a in Router A in Figure 2.1. Figure 4.1 illustrates the timing diagram for Interface a. Let $T_{b,i}$ denote the ith busy period during which Interface a is in the active mode, where $i \geq 1$. After $T_{b,i}$, Interface a switches to the sleep mode and stays in the sleep mode for a power saving period $T_{ps,i}$ (consisting of multiple sleep periods $s_{i,1}$, $s_{i,2}$, $s_{i,3}$, ...). Because Interface a alternatively stays in the busy and power saving periods, from the alternating renewal process [15], the power saving ratio R_{ps} can be expressed by

$$R_{ps} = \frac{E[T_{ps,i}]}{E[T_{b,i}] + E[T_{ps,i}]}.$$

Let P_{ps} denote the steady-state probability that Interface a is in the sleep mode. Then we have

$$P_{ps} = \lim_{t \to \infty} \Pr[\text{Interface a is in the sleep mode at time } t].$$

Let λ denote the packet arrival rate from the switch fabric to Interface a, and μ denote the service rate of a Tx. According to the M/G/1 (E, MV) model [16], we have

$$P_{ps} = 1 - \frac{\lambda}{\mu}.$$

Based on the key renewal theorem [15], we can know that

$$R_{ps} = P_{ps} = 1 - \frac{\lambda}{\mu}. \tag{4.1}$$

From (4.1), it is clear that the power saving ratio R_{ps} is independent of the length of the T_s timer.

4.2 Sleep Timer Selection

In the PSR mechanism, a larger sleep timer T_s results in longer packet delay time. In this section, we study how to set up the T_s timer for PSR to avoid unreasonable packet delay time.

Consider an interface of a router is in heavy traffic load and the PSR mechanism is not exercised. Let D^* denote the packet delay time when the interface is in heavy traffic load. Note that D^* is considered as the packet delay time constraint D^* for the PSR mechanism to select the T_s timer. As defined in Section 4.1, in the M/G/1 (E, MV) model, the service rate of a Tx is μ. Let $E[S^2]$ denote the second moment of the service time distribution. Suppose that the packet arrival rate to the interface in heavy traffic load is λ^*. From [4], we have

$$D^* = \frac{\lambda^* E[S^2]}{2(1 - \frac{\lambda^*}{\mu})} + \frac{1}{\mu}. \tag{4.2}$$

When the interface is in light traffic load, we can exercise the PSR mechanism to save router's energy consumption. Let D denote the packet delay time when we exercise the PSR mechanism in light traffic load. Suppose that the sleep period (i.e., the T_s timer) is an exponential distribution with mean $E[T_s] = 1/\lambda_s$. From the M/G/1 (E, MV) model [16], based on the packet arrival rate λ, we have

$$D = \frac{\lambda E[S^2]}{2(1 - \frac{\lambda}{\mu})} + \frac{1}{\mu} + \frac{1}{\lambda_s}. \tag{4.3}$$

We select the T_s timer to satisfy the following condition

$$D = D^*. \tag{4.4}$$

Therefore, the packet delay time is bounded by D^*. From (4.2) and (4.3), we can rewrite (4.4) as

$$\frac{\lambda E[S^2]}{2(1 - \frac{\lambda}{\mu})} + \frac{1}{\mu} + \frac{1}{\lambda_s} = \frac{\lambda^* E[S^2]}{2(1 - \frac{\lambda^*}{\mu})} + \frac{1}{\mu}.$$

Then we have

$$\lambda_s = \frac{2(1 - \frac{\lambda^*}{\mu})(1 - \frac{\lambda}{\mu})}{\lambda^* E[S^2](1 - \frac{\lambda}{\mu}) - \lambda E[S^2](1 - \frac{\lambda^*}{\mu})}. \tag{4.5}$$

Based on the equation (4.5), we can use λ^*, λ, $E[S^2]$, and μ to calculate the corresponding λ_s value (i.e., $1/E[T_s]$) and generate the length of the T_s timer that satisfies the $D = D^*$ condition.

4.3 Switch-On Overhead

In the PSR mechanism, we dynamically turn on and off the interfaces for the router to save its energy consumption. However, turning on an interface causes extra energy consumption for the router, called "switch-on overhead". In this section, we propose an analytical model to derive the switch-on overhead for the PSR mechanism.

Consider an arbitrary interface in a router. During the power saving period $T_{ps,i}$ (for $i \geq 1$), let N denote the number of times for the router to switch the interface on. Based on the M/G/1 (E, MV) model in Section 4.1, we can know that N is equal to the number of sleep periods during $T_{ps,i}$. In other words, the $T_{ps,i}$ period consists of N sleep periods $s_{i,1}$, $s_{i,2}$, ..., $s_{i,N}$. Let t_a denote the inter-packet arrival time. In the M/G/1 (E, MV) model, t_a is exponentially distributed with mean $1/\lambda$. Suppose that the sleep period is a general distribution with mean $1/\lambda_s$, density function $f(t)$, and Laplace transform $f^*(s)$. Consider a sleep period $s_{i,j}$ in $T_{ps,i}$ (where $1 \leq j \leq N$). Let α denote the probability that there is no packet arrival in $s_{i,j}$. Then we have

$$\begin{aligned}\alpha = \Pr[t_a > s_{i,j}] &= \int_{t_a=0}^{\infty} \int_{s_{i,j}=0}^{t_a} f(s_{i,j}) \lambda e^{-\lambda t_a} ds_{i,j} dt_a = \lambda \left[\frac{f^*(s)}{s} \right] \Bigg|_{s=\lambda} \\ &= f^*(\lambda). \end{aligned} \tag{4.6}$$

Applying (4.6), we have the switch-on overhead as

$$\begin{aligned} E[N] &= \sum_{i=1}^{\infty} i \Pr[N = i] = \sum_{i=1}^{\infty} i \alpha^{i-1}(1-\alpha) = \frac{1}{1-\alpha} \\ &= \frac{1}{1-f^*(\lambda)}. \end{aligned} \tag{4.7}$$

Chapter 5

Performance Evaluation

In this section, we investigate the performance of the PSR mechanism in terms of the power saving ratio R_{ps}, the rerouting ratio R_r, the packet delay time D, and the switch-on overhead $E[N]$. In Section 5.1, we use an example to show the high energy consumption for an interface in a router. Then, in Section 5.2, we develop the simulation model based on discrete-event approach, which is widely used in many networking researches (e.g., [9][10]). The details of the simulation model is also described. Finally, in Section 5.3, the simulation results for the PSR mechanism is presented.

5.1 Power Consumption of A Router

As measured by [2], Tables 5.1, 5.2, and 5.3 show the power consumption of modules of Cisco 12000 Series routers. In Table 5.1, we show the relationship between the average power consumption and the number of slots of a Cisco 12000 Series router. Obviously,

Table 5.1: The power consumption of chassis of Cisco 12000 Series Routers

Chassis power consumption	Cisco 12000 Series 16-Slot Chassis	Cisco 12000 Series 10-Slot Chassis	Cisco 12000 Series Series 6-Slot Chassis	Cisco 12000 Series Series 4-Slot Chassis
Average Power (watt)	4212 watts	2430 watts	1630 watts	1280 watts

Table 5.2: The power consumption of Route Processor of Cisco 12000 Series Routers

Route Processor power consumption	12000 Series Performance Route Processor-1	12000 Series Performance Route Processor-2
Average Power (watt)	60 watts	60 watts

we can see that more slots for a router consume more energy. In Table 5.2, we show that different types of processors for a Cisco 12000 Series router have the same energy consumption. Note that there are only two types of processors can be used for the Cisco 12000 Series router. In Table 5.3, we show the energy consumption of the two models for the Cisco 12000 Series router, i.e., 4-Port GE ISE Line Card (1 Gbps) and 1-Port GE ISE Line Card (10 Gbps). Table 5.4 shows an example of the energy consumption of different components for the service provider edge router. In Table 5.4, we can find that the Ethernet Line Cards consumes 34.5% of power of a router. Therefore, we can save much energy by switch the interface to the sleep or forbidden mode.

5.2 Simulation Model

In the simulation model, we simulate the operation behavior of an interface of a router. We define three types of events listed as follows:

Table 5.3: The power consumption of Ethernet Line Cards of Cisco 12000 Series Routers

Ethernet Line Cards power consumption	4-Port GE ISE Line Card (1 Gbps)	1-Port GE ISE Line Card (10 Gbps)
Average Power (watt)	106 watts	196 watts

Table 5.4: An example of service provider edge router

	Chassis	Route Processor	Ethernet Line Cards	
Product	Cisco 12000 Series-10 slots	12000 Series Performance Route Processor-1	4-Port GE ISE Line Card (1 Gbps)	1-Port 10-GE ISE Line Card (10 Gbps)
Count	1	1	5	4
Power (watt)	2430 watts	60 watts	106 watts	196 watts
Percentage	63.9%	1.5%	34.5%	

- The **PACKET_ARRIVAL** event represents that a packet arrives to the interface.
- The **PACKET_DEPARTURE** event represents that a packet departs from the interface.
- The **SLEEP_END** event represents that a sleep period terminates.

The following variables are used in the simulation model:

- $Vacation$ stores the mode of an interface.
- L stores the number of packets in the buffer.

The following counters are used in our simulation model to calculate the output measures:

- N counts the total number of **PACKET_ARRIVAL** events.
- $N\_departure$ counts the total number of packet departures.
- $N\_rerouting$ counts the total number of rerouting packets.
- $Service\_time$ counts the total time of serving packets.
- $Vacation\_time$ counts the total time of the interface in the sleep mode or forbidden mode.
- $Delay\_time$ counts the total packet delay time.
- N_s counts the total number of sleep periods.
- N_ps counts the total number of power saving periods.

We repeat the simulation runs until N exceeds 5,000,00 to ensure the stability of simulation results. Figure 5.1 illustrates the details of our simulation model. Then we can calculate four output measures for the PSR mechanism, including the sleeping time ratio R_{ps}, the rerouting ratio R_r, the packet delay time D, and the switch-on overhead $E[N]$, as follows:

$$R_{ps} = \frac{Service\_time}{Service\_time + Vacation\_time},$$
$$R_r = \frac{N\_rerouting}{N},$$
$$D = \frac{Delay\_time}{N\_departure},$$
$$E[N] = \frac{N\_s}{N\_ps}.$$

5.3 Simulation Results

In this section, we investigate the performance for the PSR mechanism in terms of $R_{ps}, R_r, D,$ and $E[N]$. The study for the input parameters λ^*, λ, and Δ are given as follows.

Effects of λ^* and λ on $R_{ps}, R_r, D, E[N]$: Figure 5.2(a) plots R_{ps} as function of λ, where we set $\mu = 600$, $\lambda^* = 300, 500$, $B = 10, \infty$, and $\Delta = 0.3$. Because the larger λ results in more packets to be served, it is less likely that the interface is in the sleep mode. Therefore, we observe that R_{ps} decreases as λ increases in Figure 5.2(a). For the same λ and limited buffer size, in figure 5.2(a), we also study the effects of λ^* on $R_{ps}, R_r, D, E[N]$. Because the larger λ^* (larger D^* and larger $E[T_s]$) results in more packets to be rerouted and less packets to be served, it is more likely that the

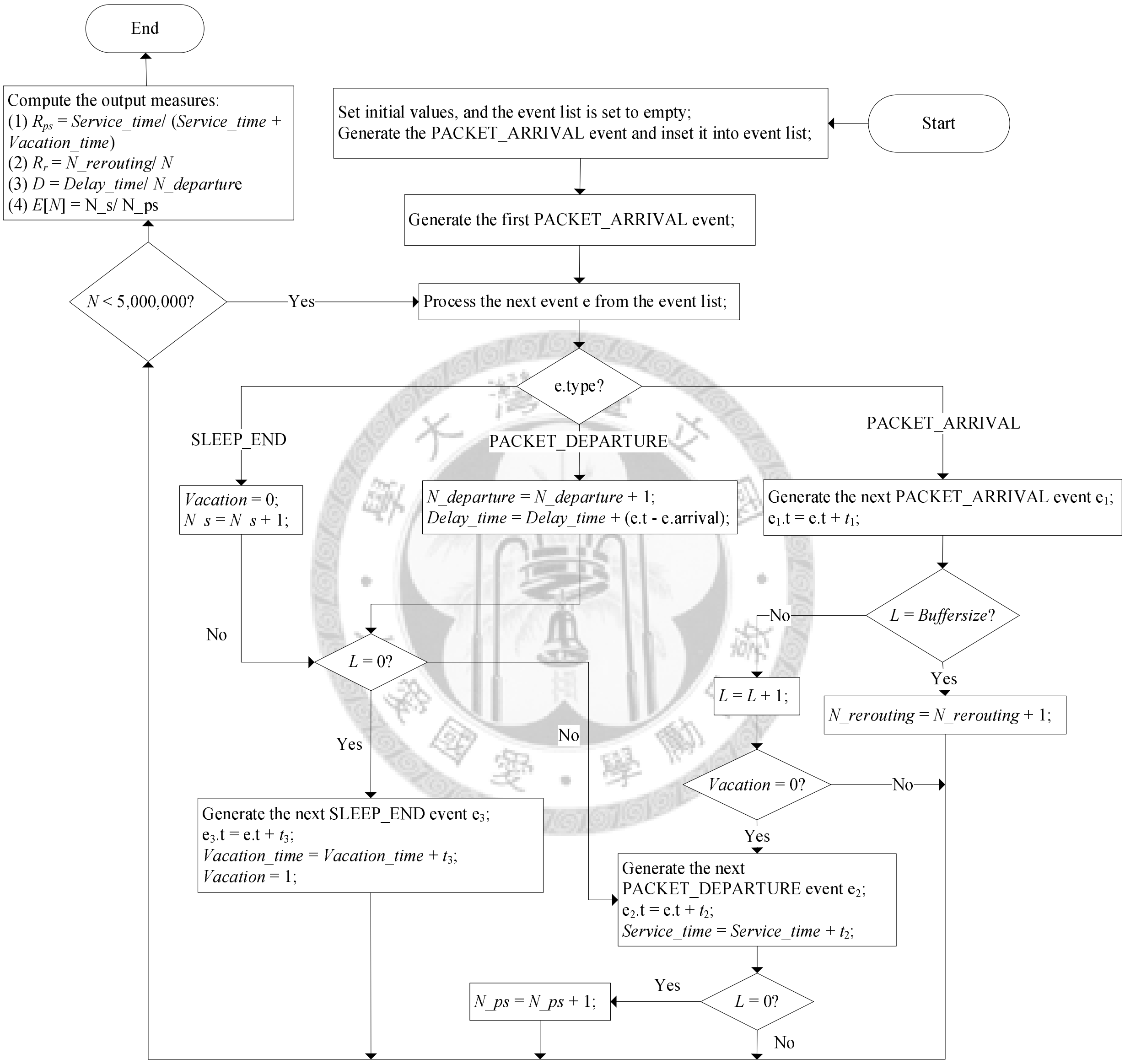


Figure 5.1: The flowchart of the simulation model

interface is in the sleep mode. Thus, we observe that R_{ps} increases as λ^* increases in Figure 5.2(a).

Figure 5.2(b) plots R_r as function of λ, where we set $\mu = 600$, $\lambda^* = 300, 500$, $B = 10, \infty$, and $\Delta = 0.3$. Because the interface don't turn to forbidden mode when $B = \infty$, the R_r is equal to 0. Therefore, we observe that $R_r = 0$ as λ increases when $B = \infty$ in Figure 5.2(b). Because the larger λ^* (larger D^* and larger $E[T_s]$) results in more packets to be rerouted, we observe that R_r increases as λ increases when $B = 10$ in Figure 5.2(b).

Figure 5.2(c) plots D as function of λ, where we set $\mu = 600$, $\lambda^* = 300, 500$, $B = 10, \infty$, and $\Delta = 0.3$. Because the larger λ^* results in less packets to be served, we observe that D decreases as λ increases when $B = 10$ in Figure 5.2(c). For the same λ, we observe that D decreases as λ increases as λ^* increases in Figure 5.2(c).

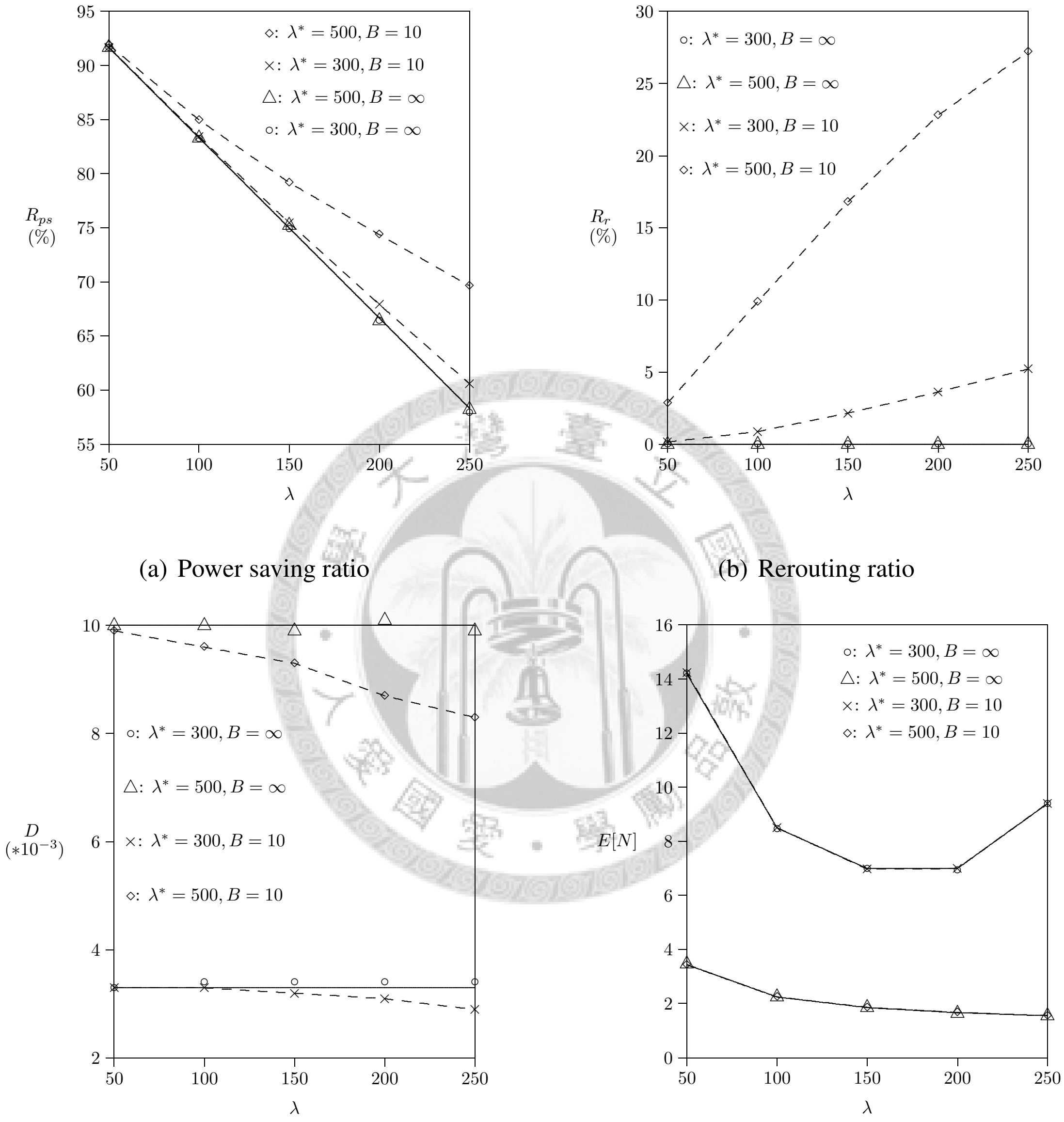
Figure 5.2(d) plots $E[N]$ as function of λ, where we set $\mu = 600$, $\lambda^* = 300, 500$, $B = 10, \infty$, and $\Delta = 0.3$. The larger λ results in the small sleep timer to be set (larger λ_s). In the simulation results, we use the exponentially distribution sleep period with mean $1/\lambda_s$. From (4.7), we can get $E[N] = 1 + \frac{\lambda_s}{\lambda}$. We can get the result that t $E[N]$ decreases in smaller λ and $E[N]$ increases in larger λ as λ increases when $\lambda^* = 300$. For the same λ, because the larger λ^* (larger D^*) result in the larger sleep timer to be set. Figure 5.2(d) shows the results that $E[N]$ decreases as λ increases when $\lambda^* = 500$. Figure 5.2(d) shows the results that $E[N]$ decreases when λ is small and $E[N]$ increases when λ is large as λ increases when $\lambda^* = 300$. Because the larger λ means that we should select small sleep timer to fit the D^*, the larger λ_s. Thus, we observe that $E[N]$ decreases as λ^* increases in Figure 5.2(d).

Effects of Δ and λ on $R_{ps}, R_r, D, E[N]$: Figure 5.3(a) plots R_{ps} as function of λ, where we set $\mu = 600$, $\lambda^* = 500$, $B = 10, \infty$, and $\Delta = 0.3, 0.5$. For the same λ, because the smaller Δ results in more packets should be reroute, it is more likely that the interface is in the sleep mode. Therefore, we observe that R_{ps} increases as Δ decreases in Figure 5.3(a).

Figure 5.3(b) plots R_r as function of λ, where we set $\mu = 600$, $\lambda^* = 500$, $B = 10, \infty$, and $\Delta = 0.3, 0.5$. For the same λ, because the smaller Δ results in more packets should be reroute, it is more likely that the interface is in the sleep mode. Therefore, we observe that R_r increases as Δ decreases in Figure 5.3(b).

Figure 5.3(c) plots D as function of λ, where we set $\mu = 600$, $\lambda^* = 500$, $B = 10, \infty$, and $\Delta = 0.3, 0.5$. For the same λ, because the smaller Δ results in the less packets will be serviced. Therefore, we observe that D decreases as Δ decreases in Figure 5.3(c).

Figure 5.3(d) plots $E[N]$ as function of λ, where we set $\mu = 600$, $\lambda^* = 500$, $B = 10, \infty$, and $\Delta = 0.3, 0.5$. Because the value of $E[N]$ only depends on packets whether arrive in sleep period or not, we observe that the Δ not affect the value of $E[N]$ in Figure 5.3(d).



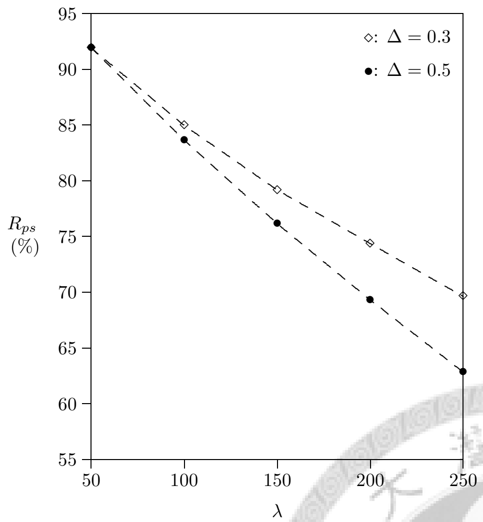
(a) Power saving ratio

(b) Rerouting ratio

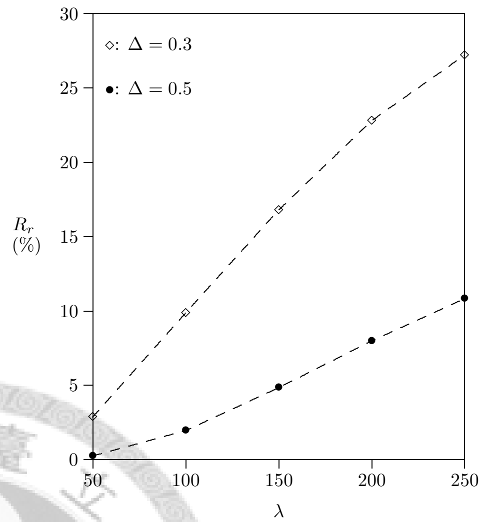
(c) Packet delay time

(d) Switch-on overhead

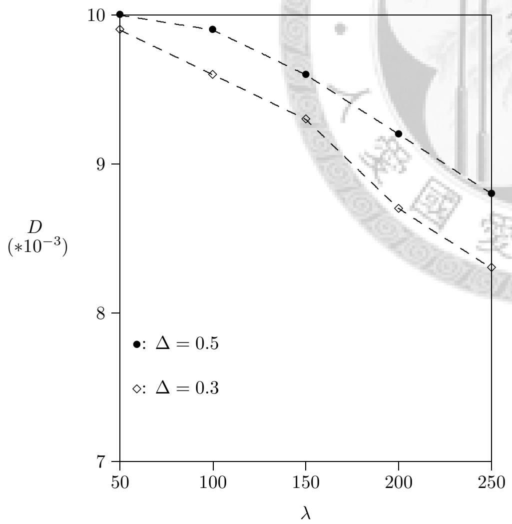
Figure 5.2: Effects of λ^* and λ on R_{ps}, R_r, D, $E[N]$



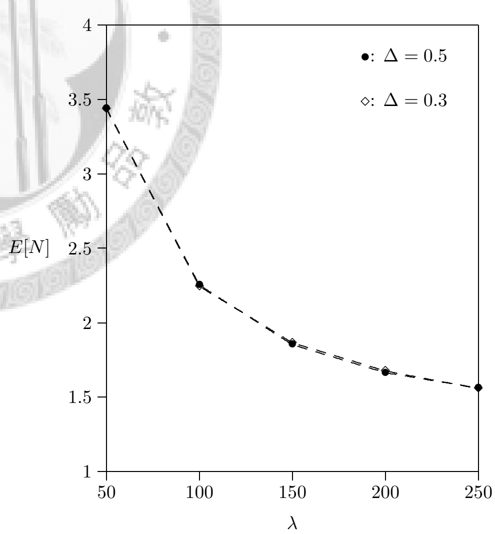
(a) Power saving ratio



(b) Rerouting ratio



(c) Packet delay time



(d) Switch-on overhead

Figure 5.3: Effects of Δ and λ on R_{ps}, R_r, D, $E[N]$

Chapter 6

Conclusion

We propose a mechanism to reduce energy consumption by taking advantage of sleep mode of routers. In our method, we turn the interface to sleep mode without learning the whole network information. Since the whole network information is not needed, the method is more practical and efficient. In our method, the router interface may be put into Active Mode, Sleep Mode, and Forbidden Mode based on buffer occupancy and packet delay time. Our mechanism causes reasonable delay by selecting proper sleep timer and can avoid buffer overflow when the interfaces are in Forbidden Mode. Besides, the router itself may also enter Sleep Mode when all of its interfaces are in Sleep Mode or Forbidden Mode and thus the router power may be saved further.

Bibliograghy

[1] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, E. Vittorini. An Energy Saving Routing Algorithm for a Green OSPF Protocol. In *IEEE INFOCOM Conference on Computer Communications Workshops*, 2010.

[2] Cisco. *Cisco website*. http://www.cisco.com.

[3] F. Mattern, T. Staake, and M. Weiss. ICT for Green - How Computers Can Help Us to Conserve Energy. In *Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking, ACM*, 2010.

[4] D. Gross and C. M. Harris. *Fundamentals of Queueing Theory, 4th edition*. Wiley Interscience.

[5] C. L. Hedrick. RFC 1058: Routing information protocol, June 1988.

[6] J. Kurose and K. Ross. *Computer Networking: A Top-Down Approach Featuring the Internet*. Addison Wesley, 3rd edition, 2004.

[7] L. Chiaraviglio, M. Mellia, F. Neri. Energy-aware Backbone Networks: a Case Study. In *IEEE ICC*, 2009.

[8] L. Chiaraviglio, M. Mellia, F. Neri. Reducing Power Consumption in Backbone Networks. In *IEEE ICC*, 2009.

[9] Lin, P., and Tu, G.-H. An Improved GGSN Failure Restoration Mechanism for UMTS. *ACM Wireless Networks*, 12(1):91–103, February 2006.

[10] Lin, Y.-B., and Yang, S.-R. A Mobility Management Strategy for GPRS. *IEEE Transactions on Wireless Communications*, 2(6):1178–1188, November 2003.

[11] M. Gupta, S. Singh. Using low power modes for energy savings in ethernet lans. In *IEEE Infocom*, 2007.

[12] J. Moy. RFC 2328: OSPF version 2, April 1998.

[13] Global Action Plan. *An Inefficient Truth*. Global Action Plan Report, http://globalactionplan.org.uk, December 2007.

[14] Y. Rekhter and T. Li. RFC 1771: A Border Gateway Protocol 4 (BGP-4), March 1995.

[15] Sheldon M. Ross. *Introduction to Probability Models*. Academic Press, 2006.

[16] N. Tian and G. Zhang. *Vacation Queueing Models-Theory and Applications*. Springer-Verlag, 2006.