修士論文

An Analysis and Evaluation of Power Saving Mechanisms for Green Office Networks

グリーンオフィスネットワークにおける省電力機構の解析と評価

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Introduction

1.1 Problem statement

Information and Communication Technologies (ICT) have become a pervasive fixture in our daily life. The use of Internet has grown an impressive 305.5% in the period $2000-2008$ [1], and cell phone use has grown approximately 300% in the period $2002-2007$ [2], with many countries having now more cell phones than people. Such an impressive increase in the number of users requires a scaling of the infrastructure to cope with the new traffic demands, which involves a larger number of devices in the infrastructure which can also provide faster communications speeds. To fulfill such requirements, devices have become more and more power hungry to the point that today we can find devices such as CISCO CRS-1 that can consume from tens of KWh up to 1 MWh.

Initially thought to be a fundamental tool in the solution to the growing energy consumption problems in every field of human activity, the ICTs have turned out to be a consumption problem of its own. The amount of electric power used to maintain the communication infrastructures is rapidly increasing every day, with current estimates in the U.S.A. [3] saying that around 2% of the total electricity consumed is used to power the Internet, and other studies in Germany [4] projecting energy consumption of IT equipment to be between 2% and 5% by 2010. Even though 2% of the U.S.A. total energy can be considered low when compared to the energy consumption of other areas, this amounts to about 74 TWh/year which makes it a high absolute value and therefore worthy of some further study towards power reduction.

The fastest growing contributor to IT energy consumption seems to be the IT equipment in office buildings [5] where high speed links are always deployed to handle rarely occurring peak loads but the average utilization is very low. This means that most of the energy used is wasted due to the energy cost of the IT equipment is not proportional to its utilization. This is particularly true in office access networks where utilization is in the range of 1% to 5% [16][17], and where faster and faster links are provided in order to improve the users' experience.

There has been a great deal of works done on conserving power consumed by IT equipment such as Energy Efficient Ethernet (EEE) [18][19] which reduces power consumption of ethernet links by dynamically varying link data rate according to the utilization, or Energy Efficient Wireless aggregation (EEW) [23] which focuses on the power consumed by office networks and tries to save the power by aggregating low-utilized users to the wireless network and turning off the switches that do not have active users. However, performance of these technologies strongly depends on several network parameters such as traffic pattern of the clients or topology of the target network. Therefore, evaluating and comparing performance of the technologies is difficult and requires a development of a power consumption model for the specific network we like to study.

In this research, we choose office networks as the target network since it is one of the largest growing area of IT and is presenting a high level of power wasting due to the over-provisioning. The objective of our research is conducting a performance evaluation and comparison of existing power saving mechanisms based on an analytical model.

1.2 Contributions

The main contributions of our research are:

- Developing an analytical model for evaluating performance of power saving mechanisms in office access networks.
- Conducting a performance evaluation and comparison of the existing mechanisms through a theoretical analysis and a simulation.

1.3 Thesis Organization

The thesis is organized as follows.

We start by introducing in the next chapter the related researches in the field of power reduction in the network environment. We will focus on Energy Efficient Ethernet, the most famous power saving technique, Energy Efficient Wireless aggregation, a mechanism proposed and developed by our laboratory and a Combination of EEE and EEW (CEW).

In the Chapter 3, we chose office access network as the target network and propose an analytical model for evaluating performance of power saving mechanisms in section 3.1. After that, we will apply the model to evaluate and compare performance of the existing power saving technologies through an theoretical analysis in section 3.2. The objects of the analysis will be EEE, EEW and CEW.

Chapter 4 describes our simulation to verify the validity of the model. The simulator implementation and simulation setup will be detailed in section 4.1 and section 4.2. The next section shows the simulation results and discussions.

We summarize the thesis in section Chapter 5 with the conclusion and future work.

Chapter 2

Energy Efficient Technologies

In recent years, research in the field of reduction of the power consumption in the network has increased enormously[19][14][21][22][23]. In this section we will focus on three technologies. The first one is Energy Efficient Ethernet which is the most famous power saving mechanism proposed by C. Gunaratne et al in 2005. The second one is Energy Efficient Wireless aggregation which has been proposed and developed by our laboratory. And the last one is CEW which has been proposed as a combination of EEE and EEW to achieve further power saving capability.

2.1 Energy Efficient Ethernet

Energy Efficient Ethernet (EEE) was first proposed by C. Gunaratne et al in 2005 as Adaptive Link Rate (ALR) [20] [19]. EEE is based on the fact that the already available different rates of Ethernet consume different amounts of power, with lower rates using less power, and its basic idea is to quickly and automatically switch the data rate of a full-duplex Ethernet link to match link utilization. EEE comprises a mechanism, which determines how the data rate is switched, and the policies, which determine when to switch the link data rate. The key performance trade-off of EEE is packet delay versus energy savings.

The EEE mechanism is defined as a 2-way MAC frame handshake, and is rooted in the auto-negotiation that Ethernet links use to agree on the data rate. The end of the link that determines a need to increase or decrease its data rate requests the change to the other end of the link using an ALR_REQUEST MAC frame. This request can be to either increase or decrease the rate. After determining the answer, the second port replies with an ALR_ACK if it agrees, or an ALR_NACK if it does not. A link might deny the request to decrease the speed of the link, but it can not deny the request to increase the speed. After this exchange there is the need of a link resynchronization. The total time of the handshake plus the resynchronization are critical to the ALR performance, because it defines the amount of delay that will be caused in then network, and although expected to be in the order of microseconds, an early implementation [20] shows that is really in terms of milliseconds.

The EEE policies are in charge of deciding when to change the rate, and assume that there are at most two possible rates. The authors introduce three policies. The first policy is based on the buffer queue length threshold with the simplest version is a single-threshold policy and more complicate one is based on a dual threshold. In the single threshold policy, the link speed is switched to high rate when buffer occupancy level equals to or exceeds a threshold value, and buffer occupancy level drops below the threshold, the link speed is switched to the low rate. In the dual threshold policy, when the buffer occupancy goes below the low threshold the link speed is reduced, and when it goes over the upper threshold the speed is increased. This policy presented a problem when traffic was smooth and at an utilization level that was over the upper threshold when in low rate and below the lower threshold when in the upper rate. To solve this they created a second policy, which is basically and addition to the previous one, where they monitor the utilization of the link by counting bytes sent in a determined interval of time. Then, beside requiring the previous conditions it also checks that the utilization is below a certain threshold. The final policy is created because the second policy might require the addition of expensive circuitry to be developed, so the authors develop a very simple timeout policy. It uses the same dual threshold, but after the link rate is increased, it stays in the high link rate for a period of time. The evaluation of this method was carried out through simulations, and it showed that up to 10% of utilization it is possible to stay in the low rate for about 40% of the time with minimum increases to delay, which, according to the author projections could render savings of up to $70 million per year in the US alone.

2.2 Energy Efficient Wireless Aggregation

In [23], Pedro et al focused on the power consumed by office networks and proposed a different approach, called Energy Efficient smart Wireless aggregation (EEW). Using the fact that the wired communication shows a very low efficiency compared to that attainable by using wireless links [**?**], EEW reduces the power consumption by moving idling or light utilization wired users to the wireless network, and turn off wired network switches that do not have active users.

EEW has two main functionalities. First is the reconfiguration system, which decides when to move users and which users to move in order to save power and reduce delay on users. Second is the procedures and infrastructure necessary to gather the information required to take the reconfiguration decisions.

The reconfiguration system are designed using policy-based approach which allows system administrators to configure the trade-off between power savings and performance disruption to users according to different preferences. The policy engine is based on a dual-threshold on the wireless network utilization. A lower threshold *APMinUtil* establishes the level of utilization until which the wireless network can still accept users. The upper threshold *APMaxUtil* defines the moment the load is considered too high, and therefore users must migrate back to the wired network. There are three policies had been proposed based on this two thresholds. The first one is *minimize user switching* which moves the minimum number of users necessary between networks while respecting the thresholds. The basic idea of this policy is to always move first the users with highest utilization in order to fulfill the required conditions taking less users. The second policy is *Minimize turning switches on or off* with the oobjective is is to reduce the number of times that switches are turned on or off. This is achieved by two methods: first, using the traffic of switches instead of individual users as the base to take decisions on who to move between networks. Second, after a switch is turned on we keep it operative for a period of time to avoid repeatedly switching the power in consecutive periods. The last policy is *Power consumption awareness*. The objective of this policy is to improve the power savings by using the network configuration that maximizes the power consumption of the devices to be turned off and minimizes the power consumption of the devices to be turned on.

The information gathering system is designed based on the SNMP monitoring architecture and is composed of three entities: *user connection agent*, *watcher agent* and *power saving controller*. The *user connection agent* is the entity in charge of surveying the current connection alternatives available to the user and handing off from one network to the other when receiving commands from the power saving controller. The *watcher agent* is the entity in charge of keeping track the number of connected users, the current utilization status of the device and each users contribution to it. It also turns on and off the device by executing commands received from the power saving controller. Finally, the *power saving controller* is the central entity where the information retrieval and policy-based link switching procedures are carried out.

2.3 CEW: a Combination of EEE and EEW

EEW has shown an impressive power saving capability by totally turning off the switches. However, performance of EEW is limited by the throughput threshold of the access point. For the network with total throughput of the clients to be much higher than throughput threshold of the access point, the probability of moving clients to the wireless network will be very small and thus the power reduced by EEW will be negligible. On the contrary, though EEE can save power with larger values of throughput of the clients, it can reduce only the power consumption of the interfaces. As the power consumption of the interfaces is much smaller than the total power consumed by the switch, the performance of EEE must be much poorer than EEW with the small value of throughput of the clients.

For these reasons, in order to improve the power saving capability we have proposed a combination of EEW and EEE, called CEW. In the CEW, clients ordinarily connect to the wired network and utilize EEE. EEW is only applied when it consumes less power than EEE. We assume that the switches can dynamically turn off the ports with no active user. This assumption is acceptable because currently there are numerous of smart ethernet transceivers available that can automatically power off after a few seconds when no power is detected on the other end of the link [28][29]. Using the assumption, we extend EEW by adding a capability of moving a part of the wired clients to the wireless network and turning the corresponding ports of the switch off. We use a power model of the switch as described in [25], then the total power consumption of the switch, E_{sw}, can be represented as follows:

$$E_{sw} = E_{base} + nE_l \tag{2.1}$$

Where E_{base} indicates the basic power consumption of the switch with no ethernet link attached, E_l is the power consumed by one link and n is the number of active links. First, we investigate under which condition EEW consumes less power than EEE. Because the total throughput of all clients connecting to the access point is limited by the throughput threshold of the access point, client i is said to be ***able to move to the wireless network*** if its arriving packet number satisfies the following condition:

$$x_i \leq \left\lfloor \frac{x_{AP}}{k} \right\rfloor \tag{2.2}$$

Assume that there are exactly l clients which are ***able to move to the wireless network***, consider the following two cases:

i) $l < k$

If we apply EEW to move l clients, which have arriving packet number satisfying (2.2), to the wireless network and turn the corresponding ports of the switch off, then the power consumption of one block in the grid is given by:

$$e_{EEW}(l) = E_{base} + lE_{wl} + E_{AP} + E_0 \tag{2.3}$$

Where E_0 denotes the total power consumed by remaining $(k-l)$ clients in the block.
On the other hand, if we use EEE to adjust data rate of the clients, then the power consumption of the block is:

$$e_{EEE}(l) = E_{base} + l\left(E_l^{low} + E_w^{low}\right) + E_0 \tag{2.4}$$

Where E_l^{low} and E_w^{low} denote the power consumption of switch's link and clients' wired NIC operating at the low data rate, respectively. The condition where EEW consumes less power than EEE is equivalent to:

$$\begin{aligned} & E_{base} + lE_{wl} + E_{AP} + E_0 < E_{base} + l\left(E_l^{low} + E_w^{low}\right) + E_0 \\ \Leftrightarrow & \begin{cases} k-1 \geq l \geq \left\lceil \frac{E_{AP}}{E_l^{low} + E_w^{low} - E_{wl}} \right\rceil \\ E_l^{low} + E_w^{low} - E_{wl} > \frac{E_{AP}}{k-1} \end{cases} \end{aligned} \tag{2.5}$$

ii) $l = k$

In this case, EEW can not only move all clients to the wireless network but also turn the switch off, therefore the power consumption of the block when using EEW is:

$$e_{EEW}^{off} = E_{AP} + kE_{wl} \tag{2.6}$$

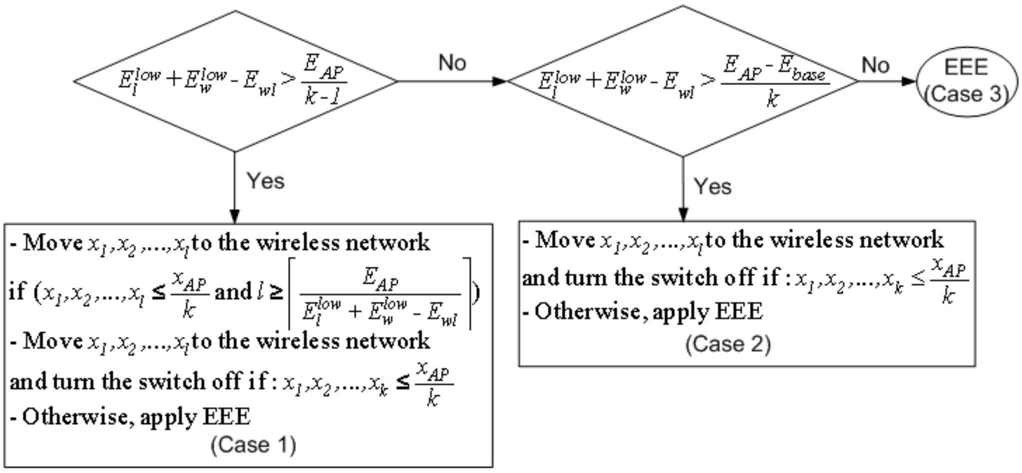


Figure 2.1: Flowchart of CEW

On the other hand, the power consumed by the block if we apply EEE to all clients is:

$$e_{EEE}^{off} = E_{base}+k\left(E_l^{low}+E_w^{low}\right) \tag{2.7}$$

The condition where EEW consumes less power than EEE thus is equivalent to:

$$\begin{aligned} E_{AP}+kE_{wl} &< E_{base}+k\left(E_l^{low}+E_w^{low}\right) \\ \Leftrightarrow \frac{E_{AP}-E_{base}}{k} &< E_l^{low}+E_w^{low}-E_{wl} \end{aligned} \tag{2.8}$$

Consequently, from (2.5) and (2.8), the policy of CEW can be divided into three cases as follows:

1. Case 1: $E_l^{low}+E_w^{low}-E_{wl}>\frac{E_{AP}}{k-1}$
   - If there are $\left\lceil \frac{E_{AP}}{E_l^{low}+E_w^{low}-E_{wl}} \right\rceil$ or more clients which ***able to move to the wireless network***, then move all of them to the wireless network and turn the corresponding ports of the switch off.
   - If all clients in the block have been moved to the wireless network then turn the switch off.

2. Case 2: $\frac{E_{AP} - E_{base}}{k} < E_l^{low} + E_w^{low} - E_{wl} \leq \frac{E_{AP}}{k-1}$

   If all clients in the block ***able to move to the wireless network*** then move them to the wireless network and turn the switch off.

3. Case 3: $E_l^{low} + E_w^{low} - E_{wl} \leq \frac{E_{AP} - E_{base}}{k}$

   Apply EEE all the time. It means that CEW is the same as EEE in this case.

The policy is summarized in Fig.2.1.

2.4 Chapter Summary

In this chapter, we have reviewed several energy efficient technologies which includes: EEW which tries to reduce power consumption of the ethernet links by dynamically varying the link data rate according to the utilization of the link, EEW which focus on the power consumed by office access networks and reduces power consumption by aggregating light utilization wired users to the wireless network and turns off the wired switches with no active users, and CEW which is a combination of EEE and EEW.

Though there are many techniques that have been proposed to reduce power consumed by network devices, performance of the techniques strongly depend on the several parameters of the target network such as network topology or traffic pattern of the clients. Therefore, unified evaluation and comparison of the techniques is difficult and requires the development of a power consumption model for the specific network we like to study. Currently, as far as we know there exist no research that fair evaluates and compares the performance of the techniques.

Chapter 3

Theoretical Analysis

3.1 An Analytical Model

In this section, we describe an analytical model for office access networks. We assume that the networks comprise both wired and wireless access and the users connect to the wired and wireless network via ethernet switches and access points, respectively.

Assume the ground of the office is represented as a rectangular with the length of L and the width of W. As each access point can only connect to clients within its radio range, we assume that the network is divided into grid and each block in the grid is served by an access point as shown in Fig. 1. Denotes R as the radio range of the access point, then the side length of the block is $R\sqrt{2}$ and the number of the blocks is $\frac{WL}{2R^2}$.

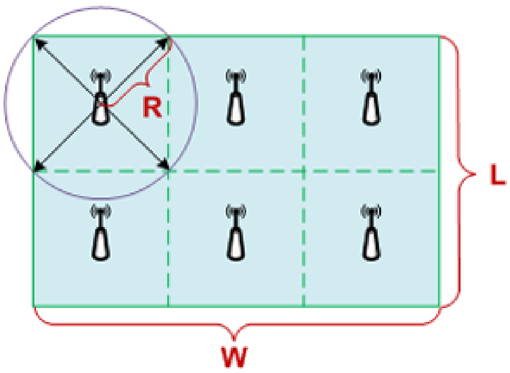


Figure 3.1: Network topology

We apply the most widely used Poisson distribution [24] to model traffic pattern of the clients. Let x_i be the number of arriving packets of client i in an interval Δt, then x_i follows Poisson distribution with an expected value of λ_i:

$$P[x_i = x] = e^{\lambda_i} \frac{\lambda_i^x}{x!} \tag{3.1}$$

Fig.3.1 shows the time plot of Poisson traffic with average throughput of *3Mbps*. For a preliminary evaluation, in this paper we assume that all clients have the same expected arriving packet number and each block is served by one switch. The analysis thus can be reduced to one

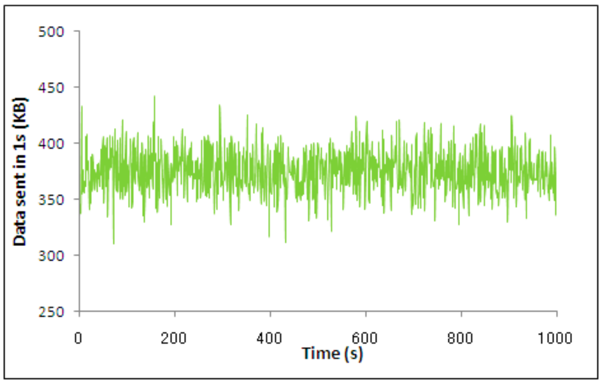


Figure 3.2: Time plot of Poisson traffic

block. Let k be the number of the clients in the block, then

$$\lambda_1 = \lambda_2 = ... = \lambda_k = \lambda \tag{3.2}$$

3.2 Theoretical Analysis of the Existing Energy Efficient Technologies

3.2.1 Analysis of EEE

Using Markov model, in [18] the authors represented the probability of having n packets in the buffer queue as:

$$P_n = \begin{cases} P_0 \rho_1^n & (0 \leq n < b) \\ \frac{P_0 \rho_1^{b-1}}{\rho + \rho/\rho_1 - 1} \left(\rho^{n-b+2} - \left(1 - \frac{\rho}{\rho_1}\right) \left(\frac{\rho_1}{1+\rho_1}\right)^{b-k+1} \right) & (n \geq b) \end{cases} \tag{3.3}$$

$$P_0 = \left(\frac{1 - \rho_1^k}{1 - \rho_1} + \frac{\rho_1^k}{1 - \rho} \right)^{-1} \tag{3.4}$$

Where

$$\rho = \frac{\lambda}{\mu}, \rho_1 = \frac{\lambda}{\mu_1} \tag{3.5}$$

μ, μ_1 are high data rate, low data rate of the switch, respectively and b is the buffer queue length threshold of the clients.

Therefore, the probability of being in low rate of one client can be calculated as:

$$\begin{aligned} P_{low-rate} &= \sum_{n=0}^{k-1} P_0 \rho_1^n \\ &= P_0 \frac{1-\rho_1^b}{1-\rho_1} \end{aligned} \tag{3.6}$$

Substituting from 3.4 to 3.6 we obtain:

$$P_{low-rate} = \frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{3.7}$$

Therefore, the power reduced by one client is:

$$\delta_{E_{link}} \frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{3.8}$$

$\delta_{E_{link}}$ denotes the power reduced by one link when varying data rate from the high level to the low level. Hence, the total power reduced by all clients is given by:

$$RE_{EEE} = k\delta_{E_{link}} \frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{3.9}$$

It is clear that RE_{EEE} is an linearly increasing function of k and the power saving potential of EEE thus linearly increases when increasing the number of clients.

To study the effects of average throughput on the performance of EEE, we use the following transformations from (3.9):

$$\begin{aligned} RE_{EEE} &= \frac{k\delta_{E_{link}}}{\dfrac{\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}}{\frac{1-\rho_1^b}{1-\rho_1}}} = \frac{k\delta_{E_{link}}}{1+\dfrac{\rho_1^b(1-\rho_1)}{1-\rho_1^b}\dfrac{1}{1-\rho}} \\ &= \frac{k\delta_{E_{link}}}{1+\dfrac{1}{\frac{1}{\rho_1}+\left(\frac{1}{\rho_1}\right)^2+..+\left(\frac{1}{\rho_1}\right)^b}\dfrac{1}{1-\rho}} \end{aligned} \tag{3.10}$$

By substituting from (3.5) in (3.10), we can easily deduce that RE_{EEE} is a decreasing function of λ. That is the power conserving potential of EEE increases with decreasing of the average throughput of clients . The maximum and minimum of the conserved power can be obtained as follows:

$$\begin{aligned} &\lim_{\lambda \to 0} RE_{EEE} \geq RE_{EEE} > \lim_{\lambda \to \infty} RE_{EEE} \\ &\Rightarrow k\delta_{E_{link}} \geq RE_{EEE} > 0 \end{aligned} \tag{3.11}$$

Power consumption of the block if using EEE, E_{EEE}, can be given by subtracting (3.9) from the total power consumption when not using EEE:

$$E_{EEE} = (E_{sw} + kE_w^{high}) - k\delta_{E_{link}} \frac{1-\rho_1^b}{1-\rho_1} \left(\frac{1-\rho_1^b}{1-\rho_1} + \frac{\rho_1^b}{1-\rho} \right)^{-1} \tag{3.12}$$

Fig.3.2.1 shows the effect of average throughput on performance of EEE with the used switch model and clients as follows. The switch was Cisco Catalyst 2970 with *24* ports and maximum power consumption of *160W*. Each link operating at 10Mbps or 1Gbps added an 0.3W or 1.8W, respectively, to the power consumption of the switch acorrding to [30]. The ethernet NICs of client were Intel Pro/1000MT with power consumption of 4W or 2.7W when operating at 1Gbps or 10Mbps, respectively. High and low data rate of clients were set to 1Gbps and 10Mbps, respectively and buffer length threshold was 30 packets. As we can see, EEE can save up to *13%* of the total when the average throughput of the clients is smaller than the low data rate (*10Mbps*). When the average throughput exceeds this point, the power reduced by EEE decreases rapidly and is negligible with the average throughput to be larger than *400Mbps*. The reason is because when the throughput is higher than the low data rate, the buffer capacity is insufficient to deal with the arrival packets and thus enlarges the probability of being in high rate of clients.

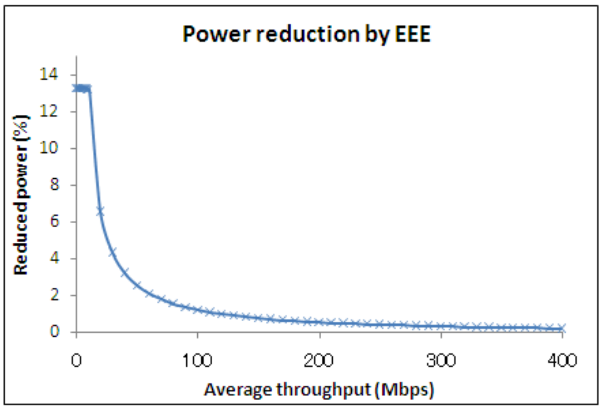


Figure 3.3: Analysis result of EEE

3.2.2 Analysis of EEW

In EEW, we move all clients to the wireless network and turn the switch off if and only if the total throughput of the clients is less than or equal to the throughput threshold of the access point. This condition can be written as follows:

$$\sum_{i=1}^{k} th_i \leq Th_{AP} \tag{3.13}$$

Where th_i denotes throughput of client i and Th_{AP} denotes throughput threshold of the access point.

Assume the average length of packets is constant and denoted as L, then the throughput of client i can be written as:

$$th_i = \frac{x_i \cdot L}{\Delta t} \tag{3.14}$$

Thus, (3.13) can be written as follows :

$$\sum_{i=1}^{k} x_i \leq \frac{Th_{AP} \cdot \Delta t}{L} = x_{AP} \tag{3.15}$$

Let $x = \sum_{i=1}^{k} x_i$ be the total number of arriving packets, then x follows Poisson distribution with expected value equal to $k\lambda$. Therefore, the probability of removing all clients to wireless and turning the switch off is represented as follows:

$$P_{sw-OFF} = \sum_{x=0}^{x_{AP}} e^{-k\lambda} \frac{(k\lambda)^x}{x!} \tag{3.16}$$

Let E_{AP}, E_{sw} be the power consumption of the access point and the switch. Let E_{wl} be the power consumption of wireless NIC and E_w^{high} be the power consumption of wired NIC operating at high data rate on the client side. Then, power consumption of the block if using EEW is given by:

$$E_{EEW} = (E_{AP}+kE_{wl}) \sum_{x=0}^{x_{AP}} e^{-k\lambda} \frac{(k\lambda)^x}{x!} + \left(E_{sw}+kE_w^{high}\right) \left(1-\sum_{x=0}^{x_{AP}} e^{-k\lambda} \frac{(k\lambda)^x}{x!}\right) \tag{3.17}$$

In the above equation, $(E_{AP}+kE_{wl})$ indicates the power consumed by the access point and the clients connecting to the wireless network, while $\left(E_{sw}+kE_w^{high}\right)$ is the power consumption of the switch and the clients connecting to the wired network. $\sum_{x=0}^{x_{AP}} e^{-k\lambda} \frac{(k\lambda)^x}{x!}$ and $\left(1 - \sum_{x=0}^{x_{AP}} e^{-k\lambda} \frac{(k\lambda)^x}{x!}\right)$ represent the probability of using the wireless and the wired network, respectively. Equation (3.17) can be simplified as:

$$\begin{aligned} E_{EEW} &= \left(E_{sw} + kE_w^{high}\right) - \left(E_{sw} + kE_w^{high} - E_{AP} - kE_{wl}\right) \sum_{x=0}^{x_{AP}} e^{-k\lambda} \frac{(k\lambda)^x}{x!} \\ &= \left(E_{sw} + kE_w^{high}\right) - \left(E_{sw} + kE_w^{high} - E_{AP} - kE_{wl}\right) \frac{\Gamma(\lfloor x_{AP} + 1 \rfloor, k\lambda)}{\lfloor x_{AP} \rfloor!} \end{aligned} \tag{3.18}$$

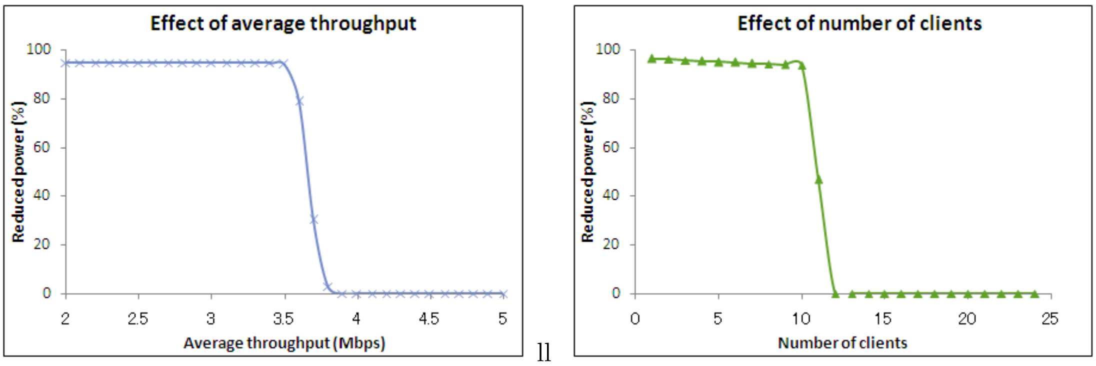
$\Gamma(x, y)$ is the incomplete gamma function. Notice that, $\left(E_{sw}+kE_w^{high}\right)$ is the total power consumption of the block when not using EEW. Thus, $\left(E_{sw} + kE_w^{high} - E_{AP} - kE_{wl}\right) \frac{\Gamma(\lfloor x_{AP}+1 \rfloor, k\lambda)}{\lfloor x_{AP} \rfloor!}$ gives us the power reduced by EEW, RE_{EEW}. Using the characteristics of the incomplete gamma function, in the following we will prove that RE_{EEW} is a decreasing function of λ.

i) RE_{EEW} is a decreasing function of λ:

$$\frac{\partial RE_{EEW}}{\partial \lambda} = -k \frac{(E_{sw} + kE_w^{high} - E_{AP} - kE_{wl})}{\lfloor x_{AP} \rfloor!} e^{-k\lambda} (k\lambda)^{\lfloor x_{AP}+1 \rfloor - 1} < 0 \tag{3.19}$$

Thus, RE_{EEW} is a decreasing function of λ. Consequently, with a fixed number of clients, the power saving potential of EEW increases when the average throughput of clients decreases. Moreover:

$$\begin{aligned} &\lim_{\lambda \to 0} RE_{EEW} \geq RE_{EEW} > \lim_{\lambda \to \infty} RE_{EEW} \\ &\Rightarrow E_{sw}+kE_w^{high}-E_{AP}-kE_{wl} \geq RE_{EEW} > 0 \end{aligned} \tag{3.20}$$



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(a) Effects of average throughput (number of clients = 6)

(b) Effects of client number (average throughput = 2Mbps)

Figure 3.4: Analysis results of EEW

Fig.3.2.2 shows the analysis results of EEW with the used model of access point and clients as follows. The access point model was Cisco Aironet 1200 with maximum power consumption of 13W and maximum data rate of 54Mbps. The throughput threshold of the access point was set to *22Mbps*. The wireless NICs of clients were Cisco Aironet 350 with maximum power consumption at transmit mode of 2.25W.

When the average of total throughput of the clients is less than the throughput threshold of the access point, the clients spend most of the time in the wireless network and thus make the switch to be turned off most of the time. Hence, the power reduced by EEW is very large. It can be observed in Fig.3.4(a) and Fig.3.4(b), when the average throughput is less than *3.5Mbps* or the number of clients is less than *10*, EEW can save more than *90%* of the total power.

However, when the average throughput or the number of clients increases and the total throughput exceeds the threshold of the access point, the power consumption of EEW increases rapidly. It can be seen that, when average throughput is larger than 4Mbps or the number is more than *12*, the power reduced by EEW almost equals to zero and using EEW can not save power consumption any more.

3.2.3 Analysis of CEW

Let $p(l)=P[\exists(x_1,x_2,...,x_l)\,|\,x_i\le\lfloor\frac{x_{AP}}{k}\rfloor(\forall i=1,2,...,l)]$, be the probability of having l clients which are ***able to move to the wireless network***. Then, $p(l)$ is calculated as follows:

$$\begin{aligned} p(l) &= \binom{k}{l}\left(\sum_{x=0}^{\lfloor\frac{x_{AP}}{k}\rfloor} e^{-\lambda}\frac{\lambda^x}{x!}\right)^l \left(1-\sum_{x=0}^{\lfloor\frac{x_{AP}}{k}\rfloor} e^{-\lambda}\frac{\lambda^x}{x!}\right)^{k-l} \\ &= \binom{k}{l} y^l (1-y)^{k-l} \end{aligned} \tag{3.21}$$

Where $y=\sum_{x=0}^{\lfloor\frac{x_{AP}}{k}\rfloor} e^{-\lambda}\frac{\lambda^x}{x!}$ represents the probability of a client being ***able to move to the wireless network***. Denotes E_{CEW} as power consumed by using CEW and $\Delta E_{EW}=E_{EEE}-E_{CEW}$ as the power that CEW reduces from EEE. In the follows, we will express ΔE_{EW} as a function of the average throughput and the number of clients for case 1 and case 2 (in case 3, $\Delta E_{EW}=0$ obviously) .

Case 1

The power that CEW reduces from EEE when we move l wired clients to the wireless network can be written as:

$$\delta_{wl}(l) = e_{EEE}(l)-e_{EEW}(l) \tag{3.22}$$

By substituting from (2.3) and (2.4) in (3.22) we have:

$$\begin{aligned} \delta_{wl}(l) &= E_{base}+l\left(E_l^{low}+E_w^{low}\right)+E_0-(E_{base}+lE_{wl}+E_{AP}+E_0) \\ &= l\left(E_l^{low}+E_w^{low}-E_{wl}\right)-E_{AP} \end{aligned} \tag{3.23}$$

Therefore, the total power that CEW reduces from EEE in case 1 can be writen as:

$$\Delta E_{EW} = \sum_{l=L_{min}}^{k-1} p(l)\delta_{wl}(l)+p(k)\delta_{off} \tag{3.24}$$

Where L_{min} denotes $\left\lceil \frac{E_{AP}}{E_l^{low}+E_w^{low}-E_{wl}} \right\rceil$. In (3.24), the first term indicates the power reduced by moving clients to the wireless network and the second term indicates the power reduced by turning the switch off. Substituting from (3.23), (3.40) and (3.21) in (3.24), we have:

$$\begin{aligned}\Delta E_{EW} &= \sum_{l=L_{min}}^{k-1} p(l)\left[l\left(E_l^{low}+E_w^{low}-E_{wl}\right)-E_{AP}\right]+p(k)\left[k\left(E_l^{low}+E_w^{low}-E_{wl}\right)+E_{base}-E_{AP}\right]\\ &= \sum_{l=L_{min}}^{k} p(l)\left[l\left(E_l^{low}+E_w^{low}-E_{wl}\right)-E_{AP}\right]+p(k)E_{base} \end{aligned} \tag{3.25}$$

Substituting from (3.21) in (3.25), we can get:

$$\begin{aligned}\Delta E_{EW} &= \sum_{l=L_{min}}^{k} \binom{k}{l} y^l(1-y)^{k-l}\left[l\left(E_l^{low}+E_w^{low}-E_{wl}\right)-E_{AP}\right]+y^k E_{base}\\ &= \left(E_l^{low}+E_w^{low}-E_{wl}\right)\sum_{l=L_{min}}^{k} l\binom{k}{l} y^l(1-y)^{k-l}-E_{AP}\sum_{l=L_{min}}^{k}\binom{k}{l} y^l(1-y)^{k-l}+y^k E_{base} \end{aligned} \tag{3.26}$$

We have:

$$l\binom{k}{l} y^l(1-y)^{k-l} = ky\binom{k-1}{l-1} y^{l-1}(1-y)^{k-l} \tag{3.27}$$

Then,

$$\sum_{l=L_{min}}^{k} l\binom{k}{l} y^l(1-y)^{k-l} = ky\sum_{l=L_{min}-1}^{k-1}\binom{k-1}{l} y^l(1-y)^{k-1-l} \tag{3.28}$$

Substituting from (3.28) in (3.26) and using the regularized incomplete beta function, (3.26) can be written as follows:

$$\begin{aligned}\Delta E_{EW} &= \left(E_l^{low}+E_w^{low}-E_{wl}\right) ky I_y(L_{min}-1, k-L_{min}+1)\\ &- E_{AP} I_y(L_{min}, k-L_{min}+1)+y^k E_{base}\\ &= f(y)\end{aligned} \tag{3.29}$$

As $f(y)$ is an increasing function of y (will be proved at *(*)*) and because y is a decreasing function of λ, ΔE_{EW} is a decreasing function of λ. This means that, the power that CEW reduced from EEE increases when the average throughput of clients decreases and:

$$\begin{aligned} &\lim_{\lambda\to 0}\Delta E_{EW} \geq \Delta E_{EW} > \lim_{\lambda\to\infty}\Delta E_{EW}\\ \Rightarrow &\left(E_l^{low}+E_w^{low}-E_{wl}\right)k-E_{AP}+E_{base} \geq \Delta E_{EW}>0 \end{aligned} \tag{3.30}$$

(*) $f(y)$ is an increasing function of y:

Let $\Delta_E = \left(E_l^{low} + E_w^{low} - E_{wl}\right)$, then:

$$\begin{aligned}\frac{\partial f}{\partial y} &= k\Delta_E\left(I_y\left(L_{min}-1, k-L_{min}+1\right) + y\frac{(1-y)^{k-L_{min}}y^{L_{min}-2}}{B\left(L_{min}-1, k-L_{min}+1\right)}\right)\\ &- E_{AP}\frac{(1-y)^{k-L_{min}}y^{L_{min}-1}}{B\left(L_{min}, k-L_{min}+1\right)} + E_{base}ky^{k-1} \qquad (3.31)\end{aligned}$$

Where, B denotes incomplete Beta function.

Using the characteristics of incomplete Beta function, we have:

$$\begin{aligned}B(L_{min}, k-L_{min}+1) &= \frac{L_{min}-1}{(L_{min}-1)+(k-L_{min}+1)}B(L_{min}-1, k-L_{min}+1)\\ &= \frac{L_{min}-1}{k}B(L_{min}-1, k-L_{min}+1) \qquad (3.32)\end{aligned}$$

Substituting from (3.32) to (3.31), we have:

$$\begin{aligned}\frac{\partial f}{\partial y} &= k\Delta_E\left(I_y\left(L_{min}-1, k-L_{min}+1\right) + y\frac{(1-y)^{k-L_{min}}y^{L_{min}-2}}{B\left(L_{min}-1, k-L_{min}+1\right)}\right)\\ &- E_{AP}\frac{(1-y)^{k-L_{min}}y^{L_{min}-1}}{B\left(L_{min}-1, k-L_{min}+1\right)}\frac{k}{L_{min}-1} + E_{base}ky^{k-1}\\ \Rightarrow \frac{\partial f}{\partial y} &= k\Delta_E\left(I_y\left(L_{min}-1, k-L_{min}+1\right)\right)\\ &+ \frac{k(1-y)^{k-L_{min}}y^{L_{min}-1}}{(L_{min}-1)B\left(L_{min}-1, k-L_{min}+1\right)}\left(-E_{AP} + \left(L_{min}-1\right)\left(E_l^{low}+E_w^{low}-E_{wl}\right)\right)\\ &+ E_{base}ky^{k-1} \qquad (3.33)\end{aligned}$$

As $L_{min} = \left\lceil \frac{E_{AP}}{\Delta_E} \right\rceil \geq \frac{E_{AP}}{\Delta_E}$, we have:

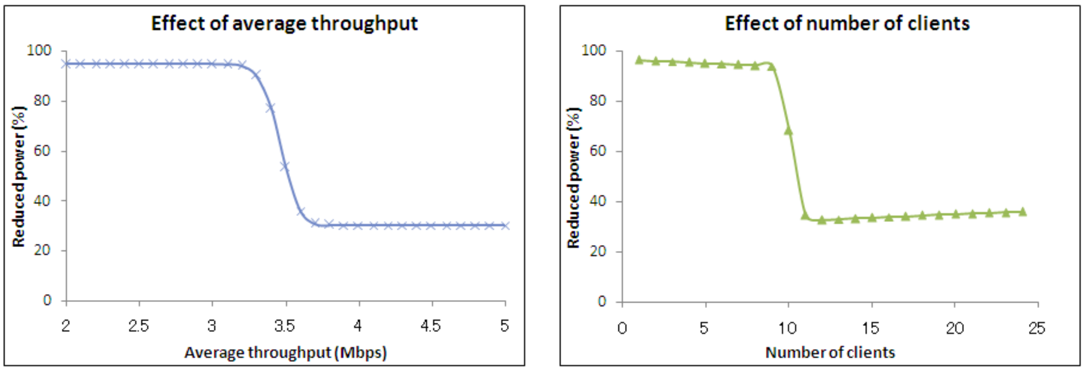
$$-E_{AP} + \left(L_{min}-1\right)\Delta_E \geq -E_{AP} + \left(\frac{E_{AP}}{\Delta_E} - 1\right)\Delta_E = -\Delta_E \qquad (3.34)$$

Substituting from (3.34) to (3.33), we obtain:

$$\frac{\partial f}{\partial y} \geq k\Delta_E\left(I_y(L_{min}-1, k-L_{min}+1) - \frac{(1-y)^{k-L_{min}}y^{L_{min}-1}}{(L_{min}-1)B(L_{min}-1, k-L_{min}+1)}\right) + E_{base}ky^{k-1} \qquad (3.35)$$

Using the transformation between incomplete game function and incomplete beta function, we have:

$$I_y(L_{min}-1, k-L_{min}+1) = \frac{B_y(L_{min}-1, k-L_{min}+1)}{B(L_{min}-1, k-L_{min}+1)} \qquad (3.36)$$



(a) Effects of average throughput (number of clients = 6)

(b) Effects of client number (average throughput = 2Mbps)

Figure 3.5: Analysis results of CEW (case 1)

From (3.35) and (3.36), we have:

$$\begin{aligned} \frac{\partial f}{\partial y} &\geq k\Delta_E \left(\frac{B_y(L_{min}-1, k-L_{min}+1)}{B(L_{min}-1, k-L_{min}+1)} - \frac{(1-y)^{k-L_{min}} y^{L_{min}-1}}{(L_{min}-1)B(L_{min}-1, k-L_{min}+1)} \right) + E_{base} k y^{k-1} \\ \Rightarrow \frac{\partial f}{\partial y} &\geq k\Delta_E \left(\frac{(L_{min}-1)B_y(L_{min}-1, k-L_{min}+1) - (1-y)^{k-L_{min}} y^{L_{min}-1}}{(L_{min}-1)B(L_{min}-1, k-L_{min}+1)} \right) + E_{base} k y^{k-1} \end{aligned} \quad (3.37)$$

Let $u(y) = (L_{min}-1)B_y(L_{min}-1, k-L_{min}+1) - (1-y)^{k-L_{min}} y^{L_{min}-1}$, then:

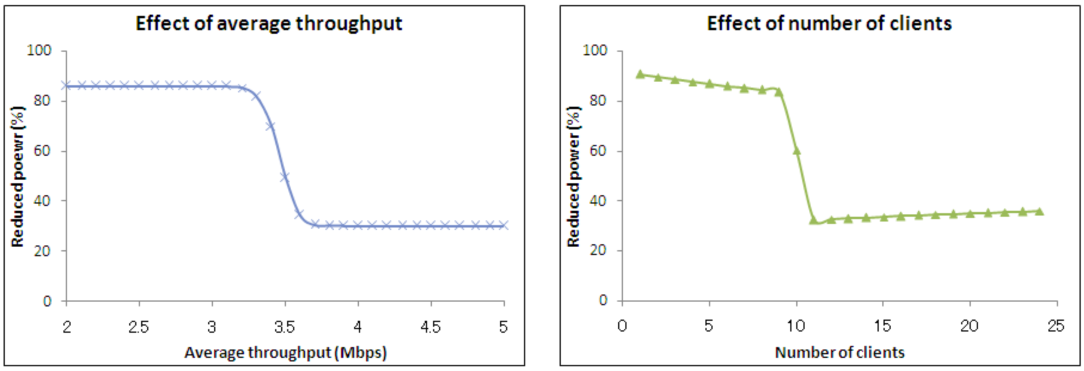
$$\begin{aligned} \frac{\partial u}{\partial y} &= (k-L_{min})(1-y)^{k-L_{min}-1} > 0 \\ \Rightarrow u(y) &\geq u(0) = 0 \end{aligned} \quad (3.38)$$

From (3.37) and (3.37)we have $\frac{\partial f}{\partial y} > 0$ and thus f is an increasing function of y.

Case 2

The power that CEW reduces from EEE when we move all clients to the wireless network and turn the switch off can be expressed as:

$$\delta_{off} = e^{off}_{EEE} - e^{off}_{EEW} \quad (3.39)$$



(a) Effects of average throughput (number of clients = 6)

(b) Effects of client number (average throughput = 2Mbps)

Figure 3.6: Analysis results of CEW (case 2)

Substituting from (2.6) and (2.7) in (3.39) we have:

$$\begin{aligned} \delta_{off} &= E_{base}+k\left(E_l^{low}+E_w^{low}\right)-\left(E_{AP}+kE_{wl}\right) \\ &= k\left(E_l^{low}+E_w^{low}-E_{wl}\right)+E_{base}-E_{AP} \end{aligned} \tag{3.40}$$

Therefore, The total power that CEW reduces from EEE in case 2 is:

$$\Delta E_{EW} = p(k)\delta_{off} \tag{3.41}$$

Substituting from (3.40) and (3.21) in (3.41), we get:

$$\Delta E_{EW} = y^k\left[k\left(E_l^{low}+E_w^{low}-E_{wl}\right)+E_{base}-E_{AP}\right] = g(y) \tag{3.42}$$

It is clear that $g(y)$ is an increasing function of y and because y is a decreasing function of λ, ΔE_{EW} is a decreasing function of λ. Thus,

$$\begin{aligned} &\lim_{\lambda\to 0}\Delta E_{EW} \geq \Delta E_{EW} > \lim_{\lambda\to\infty}\Delta E_{EW} \\ \Rightarrow &\left(E_l^{low}+E_w^{low}-E_{wl}\right)k-E_{AP}+E_{base} \geq \Delta E_{EW} > 0 \end{aligned} \tag{3.43}$$

Fig.3.5(a) and Fig.3.5(b) show the effects of the average throughput and the number of clients on the performance of CEW in case 1, respectively. The graphs were obtained using the same switch and wired NICs as in (3.2.1), and a access point and wireless NICs as in (3.2.2).

Fig.3.5(a) shows the effect of average throughput on the performance of EEW in case 1 with the number of clients was set to *6*. It can be observed from Fig.3.5(a) that, CEW can save more than *90%* of the total power consumption when the average throughput of clients is less than *3Mbps*. When the average throughput is higher than this value, the power reduced by CEW dereases rapidly with the same reason as explained in (3.2.2). When the average throughput is larger than *3.5Mbps*, the reduced power decreases to *20Mbps* and this value changes slightly with increase of the average throughput.

Fig.3.5(b) shows the effects of the number of clients on the power saved by CEW in case 1 with the average throughput of *2Mbps*. We can see that, the reduced power is very large with the number of clients to be smaller than *9*. The reason is because with these values of the number of clients, the average throughput of the clients is smaller than the threshold of moving clients to the wireless and thus enlarges the probability of applying EEW. The increase of the number of clients decreases the throughput threshold of moving clients to the wireless network and thus decreases the probability of applying EEW. When the number of the clients is larger than *10*, the threshold becomes much smaller than the average throughput of the clients and the clients spend most of the time in the wired network. The power reduced by CEW thus becomes small.

The analysis of CEW in case 2 are shown in Fig.3.6(a) and Fig.3.6(b). We can see that the obtained shapes of the graphs in case 2 are similar to that of the case 1. It is due to the power reduced by moving clients to the wireless network is negligible compared with that of turning the switch off.

3.2.4 Comparison of EEE, EEW and CEW

Using the previous analysis results, we proceed to realize a performance comparison of EEW, EEE and CEW with the parameters of interest including the average throughput and the number of clients. The switch model used was Cisco Catalyst 2970 with 24 ports and maximum power consumption of *160W*. In [30], the authors showed that each link operating at *10Mbps* or *1Gbps* added an *0.3W* or *1.8W*, respectively, to the power consumption of the switch. The access point model used was Cisco Aironet 1200 with maximum power consumption of *13W* and maximum data rate of *54Mbps*. The ethernet NICs of clients were Intel Pro/1000MT with power consumption of *4W* or *2.7W* when operating at *1Gbps* or *10Mbps*, respectively. The wireless NICs of clients were Cisco Aironet 350 with maximum power consumption at transmit mode of *2.25W*. High and low data rate of clients were set to *1Gbps* and *10Mbps*, respectively and buffer length threshold was *30 packets*.

i) Effects of throughput of clients

Fig. 3.7(a) shows the effects of the average throughput of clients on the performance of EEW, EEE and CEW. In the figure, the blue line indicates the power reduced by EEE, the green line shows the power reduced by EEW and the red line represents the power reduced by CEW.

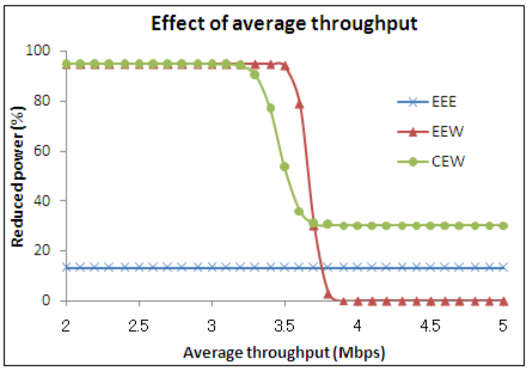
We can see that when the average of total throughput of the clients is less than the throughput threshold of the access point, the power reduced by EEW is very large due to the high probability of turning the switch off. The power reduced by CEW is approximate to the power reduced by EEW. The reason is because the average throughput is smaller than the threshold to moving lcients to the wireless network and thus EEW is applied most of the time. It also can be seen that, EEE can save only *20%* of the total and this value is very small compare with that of EEW and CEW. The reason is because EEE can reduce only the power consumed by the interfaces and it is small compare with the total power consumed by the switch.

However, as explained in (3.2.2), when the average of total throughput of the clients exceeds the throughput threshold of the access point, the performamce of EEW decreases rapidly and the power reduced by EEW becomes less than that of EEE with the average throughput of each client to be higher than *3.8Mbps*. Similarly, with the average throughput above this value, the power reduced by CEW almost equals to that of EEE. The reason is because the average throughput of the client is higher than the threshold to move to the wireless network and thus only EEE is applied. The difference between power reduced by CEW and EEE is because CEW has added a cabability to turn off un-active ports of the switch.

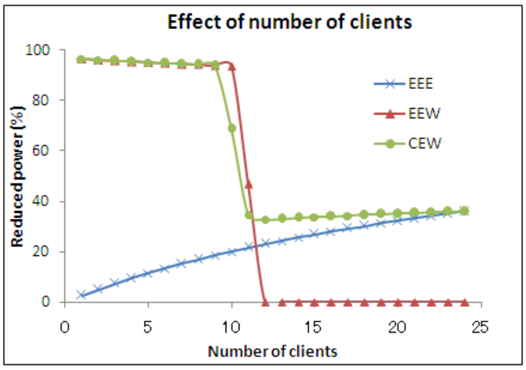
ii) Effects of number of clients

From fig. 3.7(b) it can be observed that, while power saving potential of EEE increases with increase of the number of clients, the opposite is true with EEW. When the number of clients is small and the total throughput of the clients is below the throughput threshold of the access point, the high probability of turning switch off enlarges the power saving potential of EEW and makes it more efficient than EEE. In this case, the change of power consumption caused by increasing the number of clients is also slight. In Fig. 3.7(b), with $k < 10$, power reduced by EEW is more than *4* times compare with EEE. With these values of number of clients, the power reduced by CEW is approximate to EEW due to the high probability of applying EEW in CEW.

However, when the number of clients increases and the total throughput exceeds the throughput threshold of the access point, the power reduced by EEW decreases rapidly. On the other hand, the power reduced if using EEE increases linearly with the number of clients and thus when the number of client is large enough, EEE will become more efficient than EEW. With the increase of the number of clients, the threshold of moving clients to the wireless decreases and thus decreases the probability of applying EEW. When the number of clients is larger than *12*, the EEW almost can not be applied and the power reduced by the CEW almost equals to the power reduced by EEE. And, as CEW has an extra capability to turn off un-active ports of the switch, the power reduced by CEW is a slight larger than that of EEE and the difference decreases with increase of the number of active clients.



(a) Effects of average throughput (number of clients = 6)



(b) Effects of client number (average throughput = 2Mbps

Figure 3.7: Comparison of EEE, EEW and CEW

3.3 Chapter Summary

In this chapter, we have proposed an analytical model for evaluating and comparing performance of energy efficient mechanisms in office networks. The model comprises a component for the network topology and a component for the traffic pattern of the clients.

Using the model, we have conducted an analysis of performance of the existing energy efficient technologies. The analysis results showed the power saving capability of each technologies with the amount of reduced power has been represented as a function of the average throughput and the number of the clients. Using the analysis results, now we can estimate amount of reduced power for a specific network environment.

We also presented a comparison of the performance of the technologies. Through the comparison results, now we can chose the optimal mechanism for each network environment.

Chapter 4

Simulation

In the analytical model, we have used the Poisson traffic to model the traffic pattern of the clients. However, as the Poisson traffic has been said to be insufficient in representing some characteristics of real network traffic such as the burstiness, in this chapter we describe a simulation to verify the validity of the model using self-similar traffic, the most closest model to the real network traffic.

4.1 Simulator Implementation

The simulator was developed based on the OMNET++ version 3.3 with INET framework.

Fig. 4.1 represents the simulator model of EEW. The simulator of EEW consists of a simulator for the client and a simulator for the control sever. For the simplicity we keep the switch and the access point unchanged. The simulator of the client contains a *EtherApp* module which realizes an application on the layer 2, a *Logical Link Control(LLC)*, a *802.11 MAC* and a *802.3 MAC* modules are simulated the same as described in the standard. The *EtherApp* module comprises three sub-modules: *Traffic Generator*, *Throughput Calculator* and *Interface Selector*. The *Traffic Generator* is in charge of generating the client's traffic which follows Poisson traffic model or self-similar traffic model. *Throughput Calculator* calculates average throughput of the clients every one second. The throughput is calculated as the total amount of data sent in one second. The *Interface Selector* receives traffic from the *Traffic Generator* and sends it to the current operating MAC interface. The simulator of control server contains of two modules: *Information Retrieval* and *Decision Making*. The *Information Retrieval* module receives information about throughput of the clients via the *Throughput Calculator* module of the clients and sends it to the *Decision Making* module. The *Decision Making* decides which interface the clients should use base on the policy.

Simulator model of EEE is shown in Fig. 4.1. The LLC module was kept unchanged from the standard while the MAC layer was modified by adding an extra *Rate Switching* module. The *Rate Switching* is in charge of switching the data rate according to the buffer queue length threshold. The used policy is single buffer queue threshold policy. the link speed is switched to high rate when buffer occupancy level equals to or exceeds a threshold value, and buffer occupancy level drops below the threshold, the link speed is switched to the low rate.

Simulator of CEW is shown in Fig. 4.1.

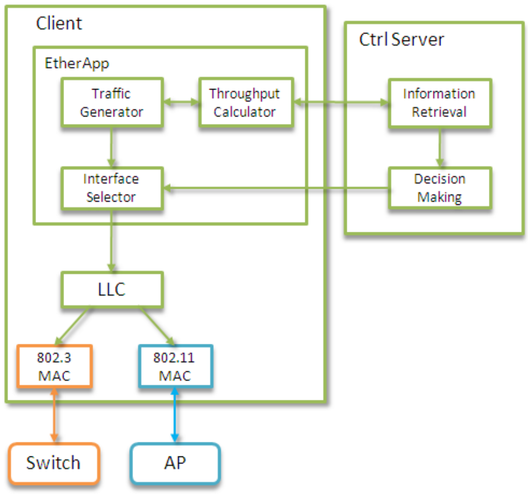


Figure 4.1: Simulator model for EEW

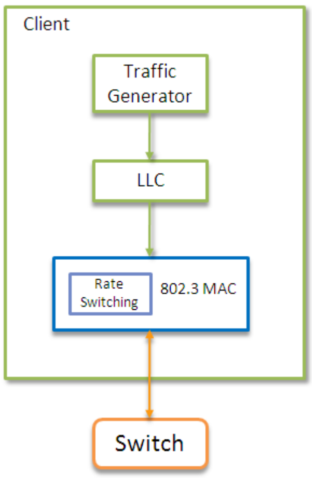


Figure 4.2: Simulator model for EEE

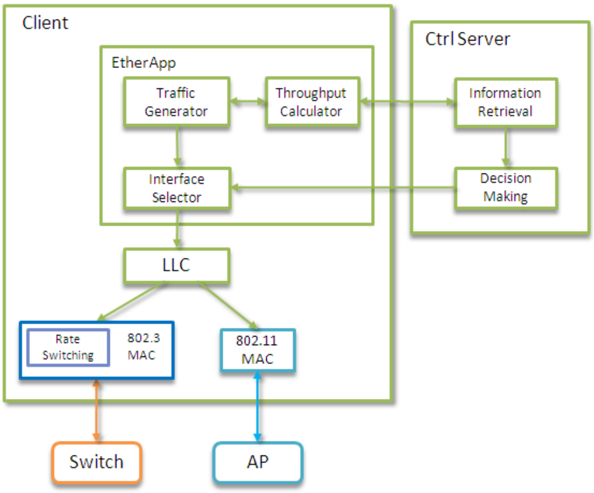


Figure 4.3: Simulator model for CEW

Simulator of CEW contains the same components as EEW with the following modifications: 1) The *802.3 MAC* module of the *Client* contains *Rate Switching* module as in the EEE simulator and 2) the *Decision Making* module of the *Control Server* is modified to realize the policy of CEW as described in 2.3.

4.2 Simulation Setup

Simulation experiments were based on two traffic patterns: Poisson traffic and self-similar traffic For the experiments described below, the used switch model was *Cisco catalyst 2970* with the total power consumption of *160W* and *24* ports. The low link data rate was set to *10Mbps* and high link data rate was set to *1Gbps*. The power consumption per one port with low data rate and high data rate were *0.3W* and *1.8W*, respectively. The *buffer queue length threshold* was set to *30* packets.

The used access point model was *Cisco Aironet* 1100 with maximum power consumption of *4.9W* and data rate of 54Mbps. The *throughput threshold* of the access point was set to *22Mbps*.

The client model contains a *Intel PRO/1000 MT* wired network interface and a *D-Link WDA-1320* wireless network interface. The power consumption of the wired network interface at the high data rate and low data rate are *5W* and *2.3W*, respectively. The power consumption of the wireless network interface is *0.82W*. The buffer length threshold was set to 30 packets and the window size of throughput calculation was set to *1s*. All experiments were run for at least 3 million packet arrivals.

Poisson traffic experiment: As Poisson traffic was used in the theoretical analysis, the simulation based on Poisson traffic with fixed packet length of 1000 bytes was conducted to study the accuracy of the theoretical analysis and the simulator. Time plots of synthetic Poisson traffics with difference throughput are shown in Fig. 4.3.1.

Self-similar traffic experiment: As Poisson traffic can not represent some characteristics of real network traffic such as burstiness, self-similar traffic was chosen to verify the validity of the model. Self-similar traffic is said to be the closest model to the real network traffic and most used in the simulation of network traffic. There are several methods to generate self-similar traffic. In our simulation, self-similar traffic was generated by aggregating multiple sub-streams, each consisting of alternating Pareto-distributed ON-OFF periods. The number of sub-streams was set to 32 and the shape parameter of each sub-stream was set to 1.4. The choice of shape parameter was prompted by measurements on actual Ethernet traffic performed by Leland et al [31]. The mean burst length of each individual sub-stream was set to 1200 packets. The uniform distribution with minimum packet size of 64 bytes and maximum packet size of 1028 bytes was chosen as the distribution of packet size. Time plots of synthetic Self-similar traffics with difference throughput are shown in Fig. 4.3.1.

The objects of the simulations were EEE, EEW and its combinations, CEW. With each scheme we conduct two experiments. With the first experiment, we keep the number of clients unchanged and evaluate the effect of the average throughput on the performance of the scheme. In this experiment, the number of client is set to 6 and the average throughput is varied from 0Mbps to 5 Mbps in case of EEW and CEW. Any throughput higher than this makes all user in the wired network at all time, and therefore there are no further change in the performance of the schemes. In the experiment on EEE, the average throughput was varied from 0Mbps to 100Mbps. The second experiment was conducted to evaluate the effect of number of clients. In this experiment, the average throughput was set to 2 Mbps. We did not conduct this evaluation on EEE because it can be obviously seen that the power consumption using EEE will linearly increase with increase of number of clients with any traffic pattern.

4.3 Simulation Results and Discussion

4.3.1 Results of Experiments on the effects of average throughput

Results from the experiments on the effects of average throughput are shown in Fig.4.3.1, Fig.4.3.1 and Fig.4.3.1. As we can see, while the results with Poisson traffic on the performance of EEW and CEW match perfecctly with the theoretical results, the results on the performance of EEE shows to parallel to the theoretical result. This is caused by the use of Markov model in the analysis of EEE.

It can be seen that, the power consumptions of the network with self-similar traffic are smaller than that with Poisson traffic when the average throughput is low. The opposite is true with high value of average throughput.

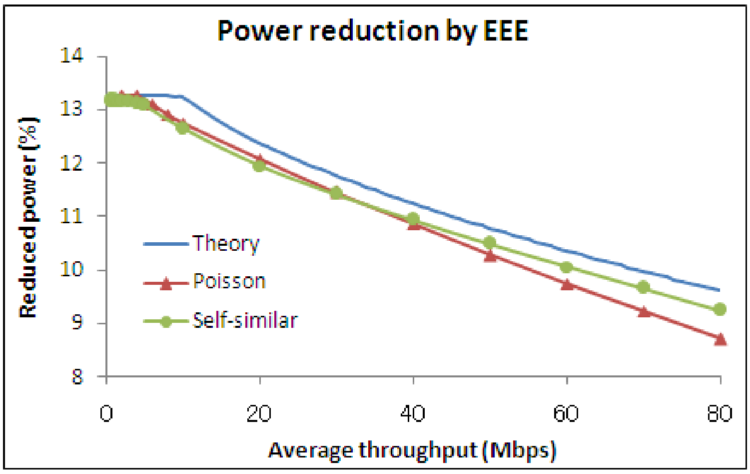


Figure 4.4: Simulation results on EEE (Effect of average throughput)

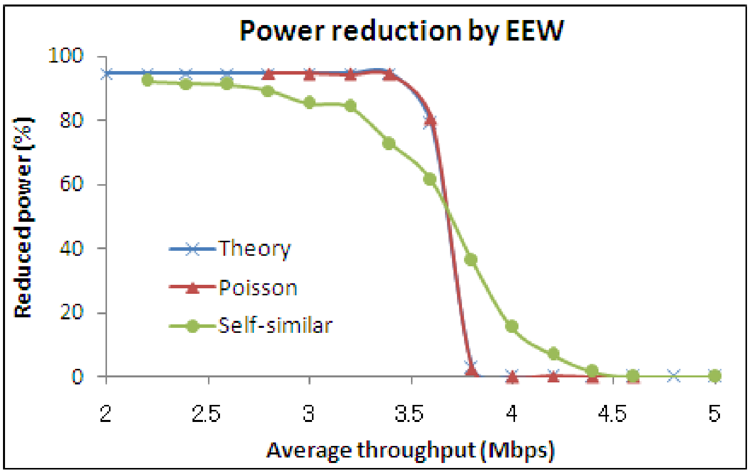


Figure 4.5: Simulation results on EEW (Effect of average throughput)

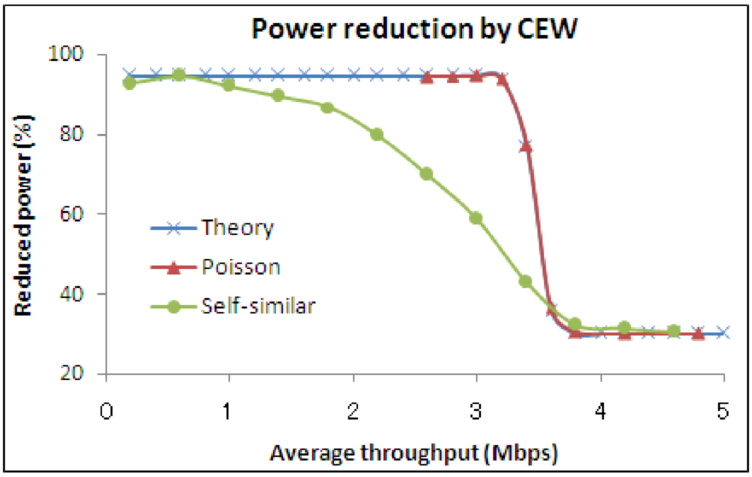


Figure 4.6: Simulation results on CEW (Effect of average throughput)

The reason can be explained as follows. As dispersion of Poisson traffic is small, when the average throughput of clients is smaller than a threshold, the throughput tends to be smaller than the threshold all the time. Consequently, In case of EEE, when the average throughput of a client is smaller than the low data rate, then the throughput tends to be smaller than the low data rate all the time. Therefore, the power reduced by switching link data rate down is very large.

In case of EEW, the average of total throughput of the clients is smaller than the threshold of the access point then the total throughput of the clients will be smaller than the threshold for the most of time and thus enlarges the probability of moving clients to the wireless network and turning the switch offe. Therefore, the power saved by EEW in this case is very large.

In case of CEW, when the average throughput of a client is smaller than the threshold of moving clients to the wireless newtwork, then the throughput of client tends to be smaller than the threshold of moving to the wireless network all the time. Consequently, the probability of applying EEW becomes high and thus the power reduced by CEW is high.

As we can see in Fig.4.7(a), with a threshold of *3.7Mbps* and the average throughput of the clients if *3.5Mbps*, the probability of the throughput of client being smaller than the threshold is large as *88%*.

On the contrary, when the average throughput of the client is larger than the threshold, the throughput of clients tends to be larger than the threshold all the time. This enlarges the time of clients being in the high data rate in case of EEE or in the wired network in case of EEW and CEW.

As we can see in Fig.4.7(b), when the average throughput of the client is *3.9Mbps*, the probability of throughput of the client being smaller than the threshold decreases rapidly to only *8.8%*.

Hence, when the average throughput of clients is larger than the threshold, the power consumption of the network increases rapidly.

On the other hand, self-similar traffic has burtiness characteristic. Therefore, despite of the average throughput of the clients is smaller or larger than the throughput threshold, the throughput of the clients contains the non-burst durations in which the throughput is smaller than the threshold and the burst durations in which the throughput is very large and becomes larger than the threshold. Consequently, the time in wireless of client in case of self-similar traffic tends to smaller than that of Poisson traffic when the average throughput is small due to the burst durations and becomes large than that of Poisson traffic when the average throughput is large due to the non-burst durations.

(a) Average throughput = 3.5Mbps (b) Average throughput = 3.9Mbps

Figure 4.7: Time plot for Poisson traffic with difference throughputs

(a) Average throughput = 3.5Mbps (b) Average throughput = 3.9Mbps

Figure 4.8: Time plot for Self-similar traffic with difference throughputs

As can be observed in Fig. 4.3.1, with the throughput threshold of *3.7Mbps*, when the average throughput of clients is *3.5Mbps*, the probability of the throughput of client being smaller than the threshold is *68%*. And even when the the average throughput of the clients increases to *3.9Mbps*, the probability is still more than *47%*. Moreover, it can be observed that the change of power consumption with self-similar traffic is smoother than that of Poisson traffic.

4.3.2 Results of Experiments on the effects of number of clients

Results from the experiments on the effects of number of clients are shown in Fig.4.3.2 and Fig.4.3.2. As can be observed from Fig.4.3.2, power reduced by EEW with self-similar traffic is smaller than that with Poisson traffic when the number of clients is small and the opposite is true with the large value of the number of clients. As explained previously, due to the small dispersion characteristic of Poisson traffic, the power reduced by EEW with Poisson traffic is larger than that with self-similar traffic when the average of total throughput of the clients is smaller than the threshold of the access point. This is equivalent to the number of clients is smaller than the ratio between the throughput threshold of the access point and the average throughput of a client. The increase of the number of clients causes the increase of the total throughput of the clients and when the average of the total throughput becomes larger than the throughput threshold of the access point the power reduced by EEW with Poisson traffic becomes smaller than that with self-similar traffic.

Fig.4.3.2 shows the results on performance of CEW. Similar to EEW, CEW can save more power with Poisson traffic when the number of clients is small but the opposite is true with increase of number of clients. The crossing point is near to the value with which the average throughput of clients is approximate to the threshold of moving clients to the wireless network. When the number of clients is smaller than this value, the threshold of moving clients to the wireless network becomes higher than the average throughput of the clients. Increase of the number of clients will decreases the throughput of moving clients to the wireless network and when the number of clients is larger than this value, the threshold of moving clients to the wireless network will be smller than the average throughput of the clients. As explained previously, when the average throughput of client is smaller than the threshold of moving clients to the wireless network, the amount of reduced power with Poisson traffic will be larger than that with self-similar traffic and the opposite will be true with the average throughput of the client to be larger than the threshold.

4.4 Chapter Summary

In this chapter, we have presented our simulation to verify the validity of the model. In order to do this, we started by describing our simulator done using OMNET version 3.3 with INET framework. The simulation was conducted base on two traffic patterns. The first one is Poisson traffic, which was used as the model for the traffic pattern of the clients and the second one is Self-similar traffic, the closest model to the real network traffic. The simulation results showed that, the amount of reduced power with self-similar traffic is smaller than that with Poisson traffic with small value of average throughput or the number of the clients. On the contrary, the amount of reduced power with self-similar traffic becomes larger than that with Poisson traffic when the average throughput or the number of client is large enough. The reason can be explained as due to the small dispersion characteristic of Poisson and the burstiness of self-similar traffic.

The trends of the results on the self-similar traffic match closely to that of theoretical analysis. Through the simulation results, the model showed to be strong and should be useful in evaluation and comparison of the existing energy efficient technologies.

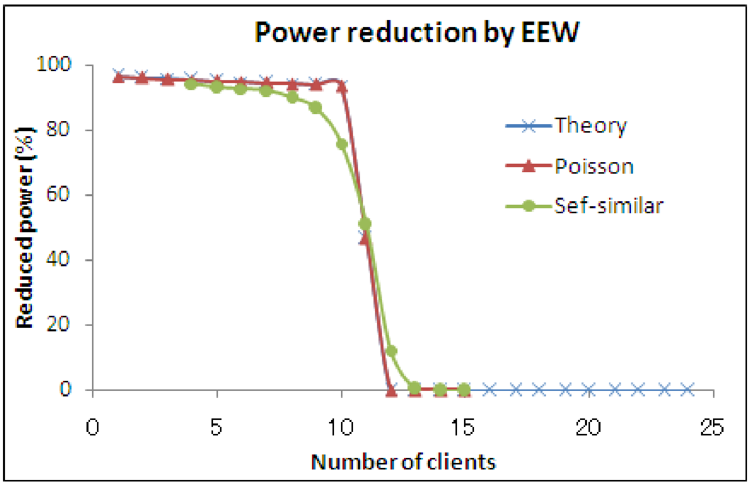


Figure 4.9: Simulation results on EEW (Effect of number of clients)

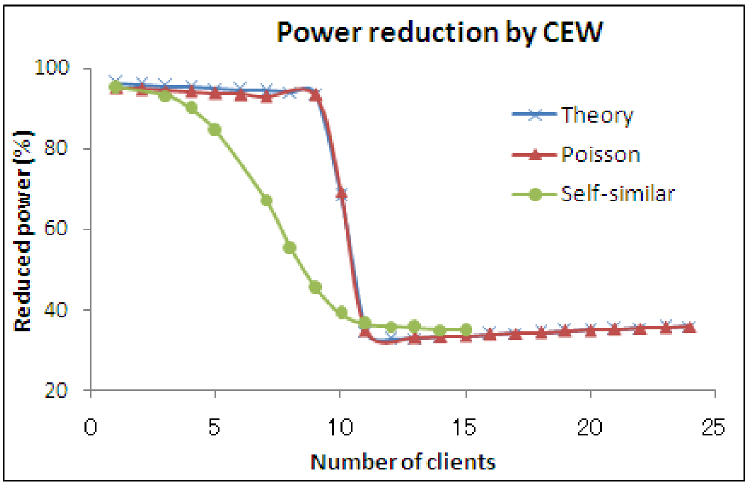


Figure 4.10: Simulation results on CEW (Effect of number of clients)

Chapter 5

Conclusion

5.1 Summary

In this thesis, we described current researches in the field of reducing power consumption in network environments. Though there has been a great deal of works done on this field, the performance of the power saving technologies strongly depend on several parameters of target networks and unified evaluation and comparison of the technologies become difficult.

In chapter 3, we have chose office network as the target network and proposed an analytical model for evaluating and comparing performance of existing power saving mechanisms. Our model contains of a component for the network topology and a component for the traffic pattern of the clients. Using the model, we have conducted a theoretical analysis of performance of several power saving mechanisms. The objectives of the analysis were: Energy Efficient Ethernet, Energy Efficient Wireless aggregation and CEW, a combination of the previous ones. Through the analysis, the amount of reduced power of each mechanism has been represented as a function of the average throughput and the number of the clients. We also conducted a comparison of these mechanisms and the results showed CEW to have better performance compare with the others.

As the Poisson traffic pattern used in the model is said to be insufficient in modeling the network traffic, in chapter 4, we have presented the simulation to study the validity of the proposed model using self-similar traffic. The simulation was conducted using a simulator done using OMNET version 3.3 with INET framework. The simulation results showed that, the power reduced by the network with self-similar traffic is smaller than that with Poisson traffic when the average throughput of clients or the number of clients is small and the opposite is true with the large value of the average throughput or the number of the clients. The validity of the model has been verified as the trends of the simulation results with self-similar traffic matched closely to the analysis results.

5.2 Future Works

In the future, we first develop the current model to make it closer to the reality. For example, the dispersion of the average throughput of the clients should be added instead of using the assumption that they are equal as currently. Next, we will evaluate not only the power saving potential but also other performance metrics such as delay, packet loss and so on. Finally, we will conduct simulations not only based on the synthetic traffic but also on the real network traffic to verify more precisely the validity of model.

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Publications

INTERNATIONAL PUBLICATIONS

[1] P. L. Nguyen, T. Morohashi, H. Imaizumi, and H. Morikawa, "A Performance Evaluation of Energy Efficient Schemes for Green Office Networks," 2nd IEEE Green Technology Conference, April 2010.

IEICE GENERAL CONFERENCES

[2] P. L. Nguyen, T. Morohashi, H. Imaizumi, M. Minami, and H. Morikawa, "A Performance Evaluation of Energy Efficient Schemes for Green Office Networks," IEICE Technical Report, CS2009-51, November 2009.

References

[1] Internet World Stats, "INTERNET USAGE STATISTICS," [Online]. Available: http://www.internetworldstats.com/stats.htm

[2] International Telecommunications Union (ITU), "ICT-Eye: Telecommunication/ICT statistics," [Online]. Available: :http://www.itu.int/ITU-D/ict/statistics/

[3] K. Kawamoto, J. Koomey, B. Nordman, R. Brown, M. Piette, M. Ting and A. Meier, "Electricity used by office equipment and network equipment in the US: detailed report and appendices," Technical Report LBNL-45917, Energy Analysis Department, Lawrence Berkeley National Laboratory, February 2001.

[4] S. Thomas and C. Barthel, "www.internet.co2? GHG Emission Trends of the Internet in Germany," [Online]. Available: http://www.iea.org/Textbase/work/2002/ictfeb02/THOMAS.PDF, 2004.

[5] K. Roth, F. Goldstein and J. Kleinman, "Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings Volume I: Energy Consumption Baseline," National Technical Information Service (NTIS), U.S. Department of Commerce, Springfield, VA 22161, NTIS Number: PB2002-101438.b, 2002.

[6] J. Roberson, C. Webber, M. McWhinney, R. Brown, M. Pinckard and J. Busch, "After-hours power status of offfice equipment and inventory of miscellaneous plug-load equipment," Technical Report LBNL-53729, Lawrence Berkeley National Laboratory, January 2004.

[7] Advanced Configuration and Power Interface Specification, Revision 3.0b [Online]. Available: http://www.acpi.info/spec.htm, October 2006.

[8] Energy Star Computer specification, Version 4.0 [Online]. Available: http://www.energystar.org.tw/pdf/Computer_Spec_Final.pdf

[19] C. Gunaratne, K. Christensen and B. Nordman, "Managing energy consumption costs in desktops PCs and LAN switches with proxying, split TCP connections, and scaling of link speed," Int. J. Network Mgmt 2005; 15:297-310.

[10] C. Gunaratne, K. Christensen, B. Nordman and S. Suen, "Reducing the Energy Consumption of Ethernet with Adaptive Link Rate (ALR)," IEEE Transactions on Computers, vol. 57, pp. 448-461, April 2008.

[11] ANSI/IEEE, "IEEE Standard for local and metropolitan area networks–Media access control (MAC) Bridges," IEEE, [Online]. Available: http://standards.ieee.org/getieee802/download/802.1D-2004.pdf

[12] P. S. Kim, A. G. Forte, A. S. Rawat, and H. Schulzrinne: "A New Seamless Handoff Mechanism for Wired and Wireless Coexistence Networks," In *Proceedings* of HPCC, Berlin, Germany, 2005.

[13] M. Inoue, K. Mahmud, H. Murakami, M. Hasegawa and H. Morikawa: "Novel out-of-band signaling for seamless interworking between heterogeneous networks," IEEE Wireless Comm. Mag., Vol. 11, Issue 2, pp. 56-63, April 2004.

[14] A. Jardosh, K. Papagiannaki, E. Belding, K. Almeroth, G. Iannaccone, and B. Vinnakota: "Green WLANs: On-Demand WLAN Infrastructure," Mobile Networks and Applications (MONET), special issue on Recent Advances in WLANs, 2008

[15] M. Gupta and S. Singh: "Greening of the Internet," In ACM SIGCOMM, Karlsruhe, Germany, August 2003.

[16] K. Christensen, C. Gunaratne and B. Nordman, "The Next Frontier for Comunications Networks: Power Management," Computer Comm, vol. 27, no. 18, pp. 1758-1770, December 2004.

[17] A. Odlyzko, "Data Networks Are Lightly Utilized, and Will Stay That Way," Rev. Network Economics, vol 2, no. 3, pp. 210-237, September 2003.

[18] "IEEE P802.3az Task Force: Energy Efficient Ethernet," [Online]. Available: http://ieee802.org/3/az/public/index.html

[19] C. Gunaratne, K. Christensen, B. Nordman and S. Suen, "Reducing the Energy Consumption of Ethernet with Adaptive Link Rate (ALR)," IEEE Transactions on Computers, vol. 57, issue 4, April 2008 pp.448-461.

[20] B. Zhang, K. Sabhanatarajan, A. Gordon-Ross and A. George: "Real-time performance analysis of Adaptive Link Rate," In *Proceedings* of 33rd IEEE LCN, Montreal, QB, Canada, October 2008.

[21] L. F. Pollo and I. Jansch-Pôrto: "A network-oriented power management architecture," In *Proceedings* of IFIP/IEEE Eighth IM, Colorado Springs, USA, March 2003.

[22] M. Gupta, S. Grover and S. Singh: "A Feasibility Study for Power Management in LAN Switches," In *Proceedings* of IEEE ICNP, p. 361–371, 2004.

[23] P. Morales, J. Ok, M. Minami and H. Morikawa, "SmartWireless Aggregation for Access Network Infrastructure Power Saving in the Office Environment," IEICE Technical Report, IN2008-209, Mar. 2009.

[24] J. Cao, W. S. Cleveland, D. Lin and D. X. Sun, "Internet Traffic Tends Toward Poisson and Independent As the Load Increases," Nonlinear Estimation and Classification, Springer, 2002, pp.83-109.

[25] G. Ananthanarayanan and R. H.Katz, "Greening the Switch," OSDI08, San Diego, CA, December 2008.

[26] S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy and D. Wetherall, "Reducing Network Energy Consumption via Sleeping and Rate Adaptation," Proc. 5th USENIX Symposium on Networked Systems Design and Implementation, Apr. 2008.

[27] T. Takiguchi, S. Saruwatari, T. Morito, S. Ishida, M. Minami and H. Morikawa, "A Novel Wireless Wake-up Mechanism for Energy-efficient Ubiquitous Networks," GreenComm09, Dresden, Germany, 18 June 2009

[28] Intel, "Intel website." [Online]. Available: http://www.intel.com/

[29] Broadcom, "Broadcom website." [Online]. Available: http://www.broadcom.com/

[30] C. Gunaratne, K. Christensen and B. Nordman, "Managing Energy Consumption Costs in Desktop PCs and LAN Switches with Proxying, Split TCP Connections, and Scaling of Link Speed," International Journal of Network Management, Vol. 15, No. 5, pp.297-310, September/October 2005.

[31] W. Leland, M. Taqqu, W. Willinger, and D. Wilson, "On the Self-Similar Nature of Ethernet Traffic (Extended Version)," IEEE/ACM Transactions on Networking, 2(1), pp. 1-15, February 1994.