A Performance Evaluation of Energy Efficient Schemes for Green Office Networks

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***Abstract*— Power consumption in office networks has become a major issue due to its running cost. In order to reduce the power consumption, several approaches have been proposed such as Energy Efficient Ethernet (EEE) and Energy Efficient Wireless aggregation (EEW). In this research, we develop an analytical model and apply the model to evaluate and compare performance of the existing technologies. The parameters of interest include the number and the average throughput of clients. Our analysis results show that EEW is more efficient than EEE with a small number of clients or low average throughput. Motivated by this result, we examine the possibility of conserving more power by introducing a combination of EEE and EEW, called EEEW. EEEW can take advantage of both EEE as well as EEW and should be very strong against the varying conditions of the network. We found that when the average throughput of clients is less than *0.5Mbps*, the combination can save more than *66%* of the power consumed by EEE. We also describe EEEWS, a combination of EEEW and link-sleep techniques which presents a further power saving potential.**

***Index Terms*— Power saving technology, energy efficient ethernet, smart wireless aggregation, wake-up module, network modeling**

I. INTRODUCTION

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]. 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. As faster devices always consume more power than the slower ones, the increase in performance has caused a substantial increase in its power consumption. Current estimates in the U.S.A. [2] saying that around *2%* or 74TWh/year of the total electricity consumed is used to power the Internet, and other studies in Germany [3] projecting energy consumption of IT equipment to be between *2%* and *5%* by 2010. The fastest growing contributor to IT energy consumption seems to be the IT equipment in office buildings [4] 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% [5][6], 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) [8][9] which reduces power consumption of ethernet links by dynamically varying link data rate according to the utilization, or Energy Efficient Wireless aggregation (EEW) 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.

Evaluating this technologies requires the development of a power consumption model for the specific network we like to study. In this paper, 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. We make three contributions: 1) developing an analytical model for office networks, 2) conducting a performance evaluation of existing technologies based on the model, 3) presenting combinations of existing technologies and evaluating the performance of the combinations.

The remainder of this paper is organized as follows. Section II describes current power saving technologies. In section III, an analytical model is developed to evaluate performance of existing energy efficient technologies. Performance of EEE and EEW will be evaluated in section IV. Section V describes a combination of EEE and EEW. We introduce a combination of EEE, EEW and a link-sleep technique in section VI and summarize this paper in section VII with the conclusion and future work.

II. RELATED WORKS

Energy Efficient Ethernet (EEE) was first proposed by C. Gunaratne et al in 2005 as Adaptive Link Rate (ALR). ALR is based on the fact that the already available different rates of ethernet links consume different amounts of power, with lower rates using less power. Its basic idea is to adaptively change the link data rate to match the utilization. ALR comprises a mechanism, which determines how the data rate is switched, and the policies, which determine when to switch the data rate. The simplest policy is a single-threshold policy which based on the buffer queue length threshold. When buffer occupancy level equals to or exceeds a threshold value, the link speed is switched to high rate, and when it drops below the threshold, the link speed is switched to the low rate.

In [10], 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 [7], 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. In EEW, clients are moved from wired network to wireless network if the total throughput of clients is less than or equals to the throughput threshold of the access point and switched back to the wired network when the total throughput exceeds the throughput threshold of the access point.

The authors in [13] presented a design and evaluation of a combination of two power saving approaches. The first focused on conserving excessive power consumption during idle times by putting idle network components to sleep. The second was based on adapting the rate of network in response to the offered workload.

Though there are many techniques that have been proposed to reduce power consumed by network devices, currently as far as we know there exist no work that fairly evaluates and compares the performance of the techniques. In order to do that, it is necessary to build a power consumption model based on a specific network.

III. 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 blok is $R\sqrt{2}$ and the number of the blocks is $\frac{WL}{2R^2}$.

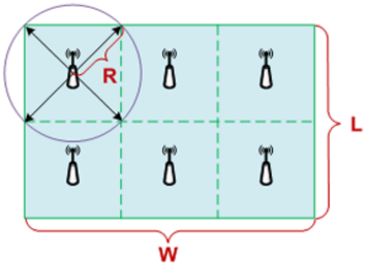


Fig. 1. Network topology

We apply the most widely used Poisson distribution [11] to model traffic pattern of 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:

$$P[x_i = x] = e^{\lambda_i}\frac{\lambda_i^x}{x!} \tag{1}$$

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

$$\lambda_1 = \lambda_2 = ... = \lambda_k = \lambda \tag{2}$$

IV. A Performance Evaluation of EEW and EEE

Applying the model described in section III, we will evaluate the power saving possibility of EEW and EEE as a function of average throughput and number of clients.

A. Power Consumption 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:

$$\sum_{i=1}^{k} th_i \leq Th_{AP} \tag{3}$$

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:

$$th_i = \frac{x_i \cdot L}{\Delta t} \tag{4}$$

Thus, (3) can be written as follows :

$$\sum_{i=1}^{k} x_i \leq \frac{Th_{AP} \cdot \Delta t}{L} = x_{AP} \tag{5}$$

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:

$$P_{sw-OFF} = \sum_{x=0}^{x_{AP}} e^{-k\lambda}\frac{(k\lambda)^x}{x!} \tag{6}$$

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:

$$\begin{aligned} E_{EEW} = {} & (E_{AP}+kE_{wl})\sum_{x=0}^{x_{AP}} e^{-k\lambda}\frac{(k\lambda)^x}{x!} \\ & + \left(E_{sw}+kE_w^{high}\right)\left(1-\sum_{x=0}^{x_{AP}} e^{-k\lambda}\frac{(k\lambda)^x}{x!}\right) \end{aligned} \tag{7}$$

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 (7) can be simplified as:

$$\begin{aligned} E_{EEW} &= \left(E_{sw}+kE_w^{high}\right) \\ &- \left(E_{sw}+kE_w^{high}-E_{AP}-kE_{wl}\right)\sum_{x=0}^{x_{AP}} e^{-k\lambda}\frac{(k\lambda)^x}{x!} \\ &= \left(E_{sw}+kE_w^{high}\right) \\ &- \left(E_{sw}+kE_w^{high}-E_{AP}-kE_{wl}\right)\frac{\Gamma(\lfloor x_{AP}+1\rfloor,k\lambda)}{\lfloor x_{AP}\rfloor !} \end{aligned} \tag{8}$$

$\Gamma(x,y)$ 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, we can prove that RE_{EEW} is a decreasing function of k and λ. This means that, with a fixed number of clients, the power saving potential of EEW increases when the average throughput of clients decreases and with a fixed value of average throughput of clients, EEW can reduce more power when decreasing the number of clients. Moreover:

$$\begin{aligned} \lim_{\lambda\to 0} RE_{EEW} &\geq RE_{EEW} > \lim_{\lambda\to\infty} RE_{EEW} \\ \Rightarrow E_{sw}+kE_w^{high}-E_{AP}-kE_{wl} &\geq RE_{EEW} > 0 \end{aligned} \tag{9}$$

B. Power Consumption of EEE

According to [8], probability of being in low rate of one client is:

$$P_{low-rate}=\frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{10}$$

Where

$$\rho=\frac{\lambda}{\mu}, \rho_1=\frac{\lambda}{\mu_1} \tag{11}$$

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 power reduced by one client is:

$$\delta_{E_{link}}\frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{12}$$

$\delta_{E_{link}}$ 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:

$$RE_{EEE}=k\delta_{E_{link}}\frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{13}$$

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 (13):

$$\begin{aligned} RE_{EEE} &= \frac{k\delta_{E_{link}}}{\dfrac{\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}}{\frac{1-\rho_1^b}{1-\rho_1}}} = \frac{k\delta_{E_{link}}}{1+\dfrac{\rho_1^b(1-\rho_1)}{1-\rho_1^b}\dfrac{1}{1-\rho}} \\ &= \frac{k\delta_{E_{link}}}{1+\dfrac{1}{\frac{1}{\rho_1}+\left(\frac{1}{\rho_1}\right)^2+..+\left(\frac{1}{\rho_1}\right)^b}\dfrac{1}{1-\rho}} \end{aligned} \tag{14}$$

By substituting from (11) in (14), 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:

$$\begin{aligned} \lim_{\lambda\to 0} RE_{EEE} &\geq RE_{EEE} > \lim_{\lambda\to\infty} RE_{EEE} \\ \Rightarrow k\delta_{E_{link}} &\geq RE_{EEE} > 0 \end{aligned} \tag{15}$$

Power consumption of the block if using EEE, E_{EEE}, can be given by subtracting (13) from the total power consumption when not using EEE:

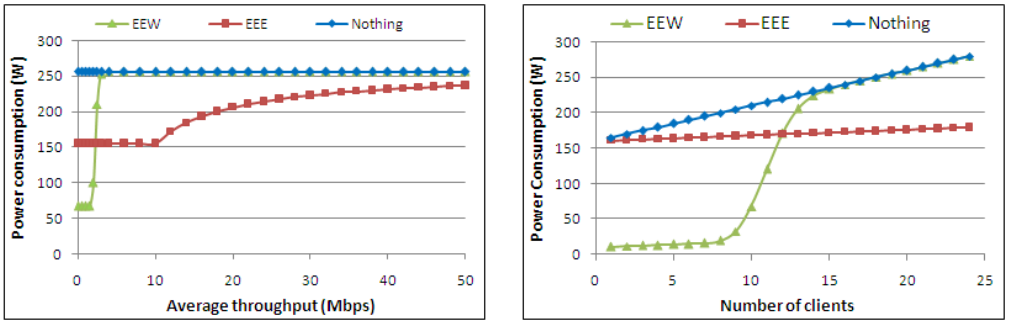
$$E_{EEE}=(E_{sw}+kE_w^{high})-k\delta_{E_{link}}\frac{1-\rho_1^b}{1-\rho_1}\left(\frac{1-\rho_1^b}{1-\rho_1}+\frac{\rho_1^b}{1-\rho}\right)^{-1} \tag{16}$$

C. Comparison of EEW and EEE

Using the previous analysis results, we proceed to realize a performance comparison of EEW and EEE 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 [17], 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. 2(a) shows the effects of the average throughput of clients on the performance of EEW and EEE. In the figure, the blue line indicates the power consumed by the block when do not apply any power saving technique, the red line shows the power consumption when using EEE and the green line represents the power consumption when applying EEW. 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. It can be observed that when the average throughput is less than *2Mbps*, EEW can save more than *70%* of the total power and more than *50%* of the power consumed by EEE. However, when the throughput



(a) Effects of average throughput (number of clients = 24)

(b) Effects of client number (average throughput = 5Mbps

Fig. 2. Effects of average throughput and number of clients on performance of EEW and EEE

increases and the total throughput exceeds the threshold of the access point, the power consumption of EEW increases rapidly and becomes more than that of EEE. When average throughput is larger than *4Mbps*, the power consumption of EEW almost equals to the total power and using EEW can not save power consumption any more.

On the other hand, the turning point of the power consumed by EEE is near by the low data rate of the switch. As we can see, power consumption of EEE is small and almost constant when the average throughput is less than the low data rate (*10Mbps*) and increases when the average throughput exceeds this point. The reason is because when the throughput is below the low data rate, the buffer capacity is sufficient to deal with the arrival packets and thus enlarges the probability of being in low rate of clients. As shown in figure 2(a), EEE can reduce more than *39%* of the total power when the average throughput is less than *10Mbps*.

ii) Effects of number of clients

From fig. 2(b) it can be observed that, while power saving potential of EEE increases with increase of the number of clients, the oppposite 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. 2(b), with $k < 10$, power consumption of EEW is less than *16%* of the total and *20%* of the power consumed by using EEE. 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. It can be observed that, with $k > 15$, the power reduced by EEW is almost zero.

V. EEEW: A COMBINATION OF EEE AND EEW

In this section, we present a combination of EEW and EEE, called EEEW. In the EEEW, 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 [15][16]. 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 [12], then the total power consumption of the switch, E_{sw}, can be represented as follows:

$$E_{sw} = E_{base} + nE_l \tag{17}$$

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.

A. Detail of EEEW

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:

$$x_i \leq \left\lfloor \frac{x_{AP}}{k} \right\rfloor \tag{18}$$

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 (18), 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:

$$e_{EEW}(l) = E_{base} + lE_{wl} + E_{AP} + E_0 \tag{19}$$

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:

$$e_{EEE}(l) = E_{base} + l\left(E_l^{low} + E_w^{low}\right) + E_0 \tag{20}$$

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:

$$\begin{aligned} & E_{base} + lE_{wl} + E_{AP} + E_0 < E_{base} + l\left(E_l^{low} + E_w^{low}\right) + E_0 \\ \Leftrightarrow \quad & \begin{cases} k-1 \geq l \geq \left\lceil \frac{E_{AP}}{E_l^{low} + E_w^{low} - E_{wl}} \right\rceil \\ E_l^{low} + E_w^{low} - E_{wl} > \frac{E_{AP}}{k-1} \end{cases} \end{aligned} \tag{21}$$

The power that EEEW reduces from EEE when condition (21) is satisfied can be written as:

$$\delta_{wl}(l) = e_{EEE}(l) - e_{EEW}(l) \tag{22}$$

By substituting from (19) and (20) in (22) we have:

$$\begin{aligned} \delta_{wl}(l) &= E_{base} + l\left(E_l^{low} + E_w^{low}\right) + E_0 - (E_{base} + lE_{wl} + E_{AP} + E_0) \\ &= l\left(E_l^{low} + E_w^{low} - E_{wl}\right) - E_{AP} \end{aligned} \tag{23}$$

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:

$$e_{EEW}^{off} = E_{AP} + kE_{wl} \tag{24}$$

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

$$e_{EEE}^{off} = E_{base} + k\left(E_l^{low} + E_w^{low}\right) \tag{25}$$

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

$$\begin{aligned} E_{AP} + kE_{wl} &< E_{base} + k\left(E_l^{low} + E_w^{low}\right) \\ \Leftrightarrow \frac{E_{AP} - E_{base}}{k} &< E_l^{low} + E_w^{low} - E_{wl} \end{aligned} \tag{26}$$

The power that EEEW reduces from EEE when condition (26) is satisfied can be expressed as:

$$\delta_{off} = e_{EEE}^{off} - e_{EEW}^{off} \tag{27}$$

Substituting from (24) and (25) in (27) we have:

$$\begin{aligned} \delta_{off} &= E_{base} + k\left(E_l^{low} + E_w^{low}\right) - (E_{AP} + kE_{wl}) \\ &= k\left(E_l^{low} + E_w^{low} - E_{wl}\right) + E_{base} - E_{AP} \end{aligned} \tag{28}$$

Consequently, from (21) and (26), the policy of EEEW 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. That is, EEEW is the same as EEE in this case.

The policy is summarized in Fig. 3.

B. Power Consumption of EEEW

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

$$\begin{aligned} p(l) &= \binom{k}{l} \left(\sum_{x=0}^{\lfloor \frac{x_{AP}}{k} \rfloor} e^{-\lambda} \frac{\lambda^x}{x!} \right)^l \left(1 - \sum_{x=0}^{\lfloor \frac{x_{AP}}{k} \rfloor} e^{-\lambda} \frac{\lambda^x}{x!} \right)^{k-l} \\ &= \binom{k}{l} y^l (1-y)^{k-l} \end{aligned} \tag{29}$$

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_{EEEW} as power consumed by using EEEW and $\Delta E_{EW} = E_{EEE} - E_{EEEW}$ as the power that EEEW 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) .

1) Case 1:

$$\Delta E_{EW} = \sum_{l=L_{min}}^{k-1} p(l)\delta_{wl}(l) + p(k)\delta_{off} \tag{30}$$

Where L_{min} denotes $\left\lceil \frac{E_{AP}}{E_l^{low} + E_w^{low} - E_{wl}} \right\rceil$. In (30), 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 (23), (28) and (29) in (30), we have:

$$\begin{aligned} \Delta E_{EW} &= \sum_{l=L_{min}}^{k-1} p(l) \left[l\left(E_l^{low} + E_w^{low} - E_{wl}\right) - E_{AP} \right] \\ &+ p(k) \left[k\left(E_l^{low} + E_w^{low} - E_{wl}\right) + E_{base} - E_{AP} \right] \\ &= \sum_{l=L_{min}}^{k} p(l) \left[l\left(E_l^{low} + E_w^{low} - E_{wl}\right) - E_{AP} \right] \\ &+ p(k) E_{base} \end{aligned} \tag{31}$$

Substituting from (29) in (31), we can get:

$$\begin{aligned} \Delta E_{EW} &= \sum_{l=L_{min}}^{k} \binom{k}{l} y^l (1-y)^{k-l} \left[l\left(E_l^{low} + E_w^{low} - E_{wl}\right) - E_{AP} \right] \\ &+ y^k E_{base} \\ &= \left(E_l^{low} + E_w^{low} - E_{wl}\right) \sum_{l=L_{min}}^{k} l \binom{k}{l} y^l (1-y)^{k-l} \\ &- E_{AP} \sum_{l=L_{min}}^{k} \binom{k}{l} y^l (1-y)^{k-l} + y^k E_{base} \end{aligned} \tag{32}$$

We have:

$$l \binom{k}{l} y^l (1-y)^{k-l} = ky \binom{k-1}{l-1} y^{l-1} (1-y)^{k-l} \tag{33}$$

Then,

$$\sum_{l=L_{min}}^{k} l \binom{k}{l} y^l (1-y)^{k-l} = ky \sum_{l=L_{min}-1}^{k-1} \binom{k-1}{l} y^l (1-y)^{k-1-l} \tag{34}$$

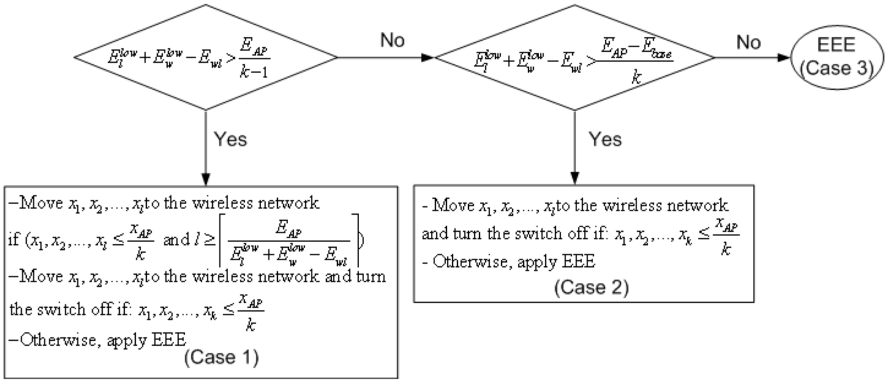


Fig. 3. Flowchart of EEEW

Substituting from (34) in (32) and using the regularized incomplete beta function, (32) can be written as follows:

$$\begin{aligned}\Delta E_{EW} &= \left(E_l^{low}+E_w^{low}-E_{wl}\right) ky I_y(L_{min-1}, k-L_{min}+1) \\ &- E_{AP} I_y(L_{min}, k-L_{min}+1) + y^k E_{base} \\ &= f(y)\end{aligned} \tag{35}$$

Using the characteristics of the regularized incomplete beta function we can prove that $f(y)$ is an increasing function of y and as y is a decreasing function of λ, ΔE_{EW} is a decreasing function of λ. This means that, the power that $EEEW$ reduced from EEE increases when the average throughput of clients decreases and:

$$\begin{aligned}\lim_{\lambda\to 0} \Delta E_{EW} &\geq \Delta E_{EW} > \lim_{\lambda\to\infty} \Delta E_{EW} \\ \Rightarrow \left(E_l^{low}+E_w^{low}-E_{wl}\right) k - E_{AP} + E_{base} &\geq \Delta E_{EW} > 0\end{aligned} \tag{36}$$

Fig. 4(a) and Fig. 4(b) show the effects of the average throughput and the number of clients on the performance of EEEW, respectively. The graphs were obtained using the same switch as in section (IV-C), but a different access point and wireless NICs with lower power consumptions. The used access point is Cisco Aironet 1100 with maximum power consumption of *4.9W*, the wireless NIC is D-Link WDA-1320 with maximum power consumption at transmit mode of *0.82W*. In the figures, the blue line indicates the total power consumed by the block when do not apply any power saving technique, the red line represents the power consumption if using EEE and the green line shows the power that EEEW reduces from EEE.

It can be observed from Fig. 4(a) that, EEEW can save more than *66%* of the power consumed by using EEE when the average throughput of clients is less than *0.5Mbps*. The difference between EEEW and EEE decreases when increasing the throughput due to the decrease of probability in moving clients to the wireless network. When the average throughput is more than *5Mbps*, the difference is almost equal to zero and EEEW is not more efficient than EEE anymore. Though EEEW is effective only when the average throughput is small, such small throughput values are pervasive in current office networks.

Fig. 4(b) shows the effects of the number of clients on the power saved by EEEW. We see that, the difference of power consumption between EEEW and EEE has a ladder-like shape. The dropping points are caused by the change of the throughput threshold of moving clients to the wireless network, $\left\lfloor \frac{x_{AP}}{k} \right\rfloor$. Notice that, $\left\lfloor \frac{x_{AP}}{k} \right\rfloor$ decreases by a ladder-like shape when k increases. Therefore, when $\left\lfloor \frac{x_{AP}}{k} \right\rfloor$ drops down it decreases the probability of moving clients to the wireless network and thus causes the suddenly decrease of the power reduced by EEEW. Figure 4(b) shows that, with average throughput of clients of 1Mbps, EEEW can save more than *32%* of the power consumed by using EEE with number of clients raging from 1 to 24.

2) Case 2: The power that EEEW reduces from EEE in case 2 is:

$$\Delta E_{EW} = p(k)\delta_{off} \tag{37}$$

Substituting from (28) and (29) in (37), we get:

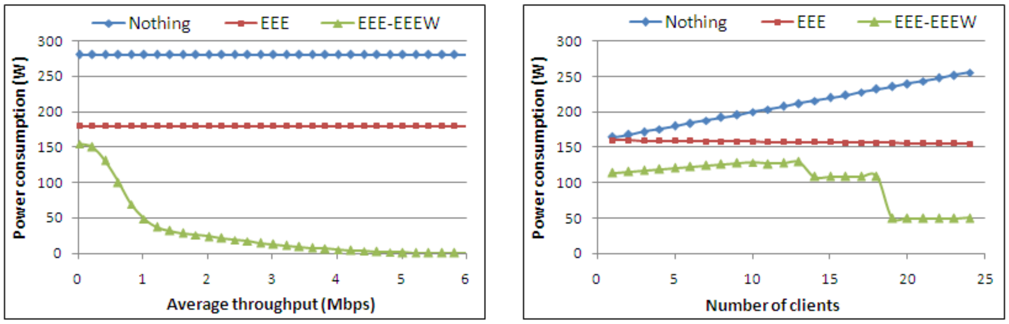
$$\Delta E_{EW} = y^k \left[k\left(E_l^{low}+E_w^{low}-E_{wl}\right)+E_{base}-E_{AP}\right] = g(y) \tag{38}$$

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,

$$\begin{aligned}\lim_{\lambda\to 0} \Delta E_{EW} &\geq \Delta E_{EW} > \lim_{\lambda\to\infty} \Delta E_{EW} \\ \Rightarrow \left(E_l^{low}+E_w^{low}-E_{wl}\right) k - E_{AP} + E_{base} &\geq \Delta E_{EW} > 0\end{aligned} \tag{39}$$

Fig. 5(a) and Fig. 5(b) show the effects of the throughput and number of clients, respectively, on the performance of EEEW in case 2. The input data is the same as in (IV-C). We can see that the 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. Similar to the case 1, power saved by EEEW increases when the throughput of clients decreases. With average throughput of clients being less than *0.5Mbps*, EEEW can saved more than *44%* of the power consumed by EEE and the saved power accounts for *28%* of the total power consumption when do not applying any power saving technique. Power consumption of EEEW is almost equal to that of EEE when the average throughput of clients is larger than *2Mbps*.

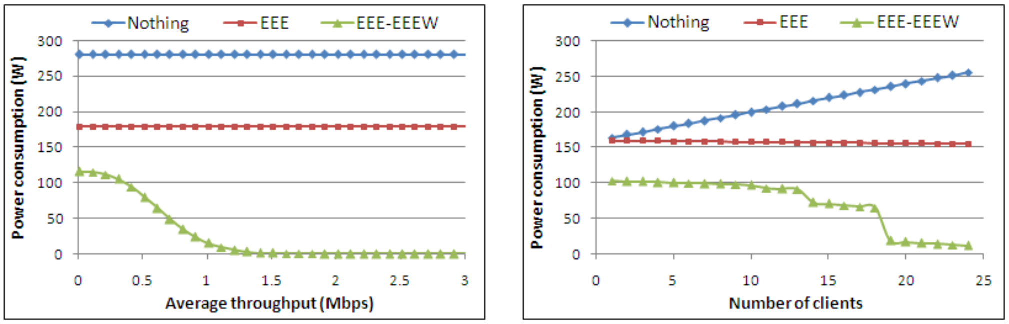
Power reduced by EEEW tends to decrease when increasing the number of clients as shown in Fig. 5(b). The obtained ladder-like shape can be explained by a similar reason as in the case 1.



(a) Effects of average throughput (number of clients = 24)

(b) Effects of client number (average throughput = 1Mbps)

Fig. 4. Effects of average throughput and number of clients on performance of EEEW (case 1)



(a) Effects of average throughput (number of clients = 24)

(b) Effects of client number (average throughput = 1Mbps)

Fig. 5. Effects of average throughput and number of clients on performance of EEEW (case 2)

VI. EEEWS: A COMBINATION OF EEE, EEW AND LINK-SLEEP TECHNOLOGY

We call technologies that enable wireless clients to operate at very low power state during idling period such as [13][14], *"link-sleep technology"*. In this section, we propose and study power saving potential of EEEWS, a combination of EEE, EEW and link-sleep technology. EEEWS is the same as EEEW except that, in EEEWS the clients will utilize link-sleep technique to operate at low power state during idle period. We call the state that clients operate at low power, a sleep state and the state that client operating at full power, an awake state. Then client i is in the sleep state if and only if the following two conditions are satisfied:

1) Its throughput is equal to 0
2) It is operating in the wireless network

In case 1, the second condition is equivalent to $x_i \leq \lfloor \frac{x_{AP}}{k} \rfloor$ and existing more than $(L_{min}-1)$ other clients j which also have arriving packet number satisfying $x_j \leq \lfloor \frac{x_{AP}}{k} \rfloor$. In case 2, the second condition means that all clients have arriving packet number being less than or equal to $\lfloor \frac{x_{AP}}{k} \rfloor$. Denotes E_{EEEWS} as the power consumed by using EEEWS and $\Delta E_{WS} = E_{EEEW} - E_{EEEWS}$, as the power that EEEWS reduces from EEEW, then ΔE_{WS} can be calculated as follows.

A. *case 1*

Denotes $p_s(i)$ as probability of client i being in the sleep state, Then:

$$\begin{aligned} p_s(i) &= P\left[(x_i=0)\cap\left(\exists(x_{j_1},x_{j_2},\ldots,x_{j_l})\,|\,x_{j_m}\leq\left\lfloor\frac{x_{AP}}{k}\right\rfloor(\forall m=1\rightarrow l)\right)\right] \\ &\quad (k-1\geq l\geq L_{min}-1;\, j_m\neq i) \\ &= P\left[x_i=0\right]P\left[\exists\left(x_{j_1},x_{j_2},\ldots,x_{j_l}\right)|\,x_{j_m}\leq\left\lfloor\frac{x_{AP}}{k}\right\rfloor(\forall m=1\rightarrow l)\right] \\ &= e^{-\lambda}\sum_{l=L_{min}-1}^{k-1}\binom{k-1}{l}y^l(1-y)^{k-1-l} \end{aligned} \tag{40}$$

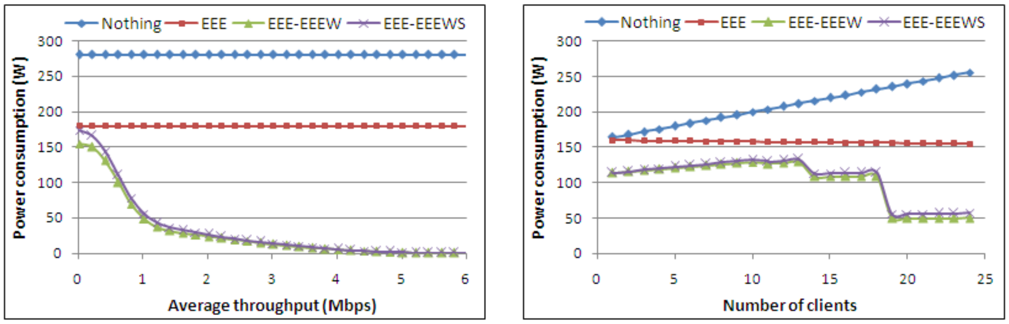
Where $y=\sum_{x=0}^{\lfloor \frac{x_{AP}}{k} \rfloor} e^{-\lambda}\frac{\lambda^x}{x!}$. Let E_{wl}^{awake} and E_{wl}^{sleep} be the power consumption of the wireless NIC at the awake and sleep state, respectively, then:

$$\Delta E_{WS} = \sum_{i=1}^{k}\left(E_{wl}^{awake}-E_{wl}^{sleep}\right)p_s(i) \tag{41}$$

Substituting from (40) in (41) we obtain:

$$\begin{aligned} \Delta E_{WS} &= k\left(E_{wl}^{awake}-E_{wl}^{sleep}\right)e^{-\lambda}\sum_{l=L_{min}-1}^{k-1}\binom{k-1}{l}y^l(1-y)^{k-1-l} \\ &= k\left(E_{wl}^{awake}-E_{wl}^{sleep}\right)e^{-\lambda}I_y(L_{min}-1,k-L_{min}+1) \end{aligned} \tag{42}$$

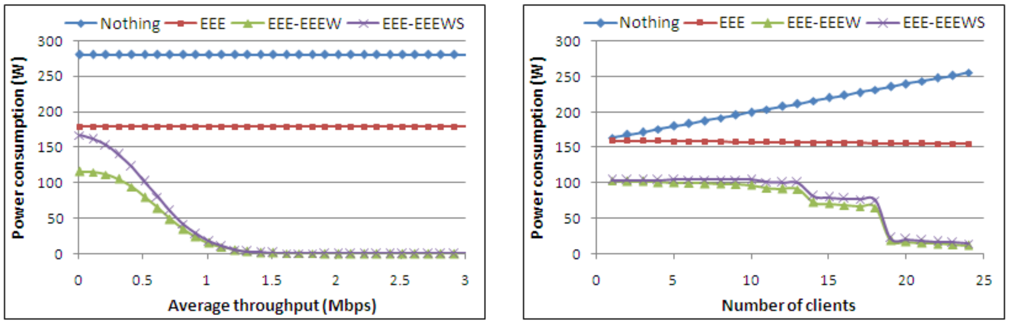
As I_y is an increasing function of y and y is a decreasing function of λ, ΔE_{WS} is a decreasing function of λ. Therefore:



(a) Effects of average throughput (number of clients = 24)

(b) Effects of client number (average throughput = 1Mbps)

Fig. 6. Effects of average throughput and number of clients on performance of EEEWS (case 1)



(a) Effects of average throughput (number of clients = 24)

(b) Effects of client number (average throughput = 1Mbps)

Fig. 7. Effects of average throughput and number of clients on performance of EEEWS (case 2)

$$\begin{aligned} \lim_{\lambda\to 0}(\Delta E_{WS}) &\geq \Delta E_{WS} > \lim_{\lambda\to\infty}(\Delta E_{WS}) \\ \Rightarrow k\left(E_{wl}^{awake} - E_{wl}^{sleep}\right) &\geq \Delta E_{WS} > 0 \end{aligned} \tag{43}$$

B. case 2

The probability of client i being in the sleep state in case 2 is given by the following equation:

$$\begin{aligned} p_s(i) &= P\left[(x_i = 0) \cap \left(x_j \leq \left\lfloor \frac{x_{AP}}{k} \right\rfloor \forall j = 1, 2, ..., k; j \neq i\right)\right] \\ &= P\left[x_i = 0\right] P\left[x_j \leq \left\lfloor \frac{x_{AP}}{k} \right\rfloor (\forall j = 1, 2, ..., k; j \neq i)\right] \\ &= e^{-\lambda} y^{k-1} \end{aligned} \tag{44}$$

The power that EEEWS reduces from EEEW is:

$$\begin{aligned} \Delta E_{WS} &= \sum_{i=1}^{k} \left(E_{wl}^{awake} - E_{wl}^{sleep}\right) p_s(i) \\ &= k \left(E_{wl}^{awake} - E_{wl}^{sleep}\right) e^{-\lambda} y^{k-1} \end{aligned} \tag{45}$$

As y^{k-1} is an increasing function of y and y is a decreasing function of λ, y^{k-1} is a decreasing function of λ. Moreover, $e^{-\lambda}$ also is a decreasing function of λ, therefore ΔE_{WS} is a decreasing function of λ, Then:

$$\begin{aligned} \lim_{\lambda\to 0}(\Delta E_{WS}) &\geq \Delta E_{WS} > \lim_{\lambda\to\infty}(\Delta E_{WS}) \\ \Rightarrow k\left(E_{wl}^{awake} - E_{wl}^{sleep}\right) &\geq \Delta E_{WS} > 0 \end{aligned} \tag{46}$$

Fig. 6(a) and Fig. 6(b) show the effects of the average throughput and the number of clients on the performance of EEEWS in case 1. The effects of the parameters on the performance of EEEWS in case 2 are shown in Fig. 7(a) and Fig. 7(b). In the figures, the blue line indicates the total power consumed by the block when do not apply any power saving technique, the red line represents the power consumption if using EEE, the green line shows the power that EEEW reduces from EEE and the violet line denotes the power that EEEWS reduces from EEE. The obtained shapes of the figures can be explained by the same reasons as in section V. It can be observed that, EEEWS presents a higher power saving potential compared with EEEW and the saved power increases when decreasing the average throughput of clients. When the average throughput is less than 0.5Mbps, the power reduced by EEEWS is larger than 109% of the power reduced by EEEW in case 1 and larger than 128% in case 2. Fig. 6(b) and 7(b) show that effect of the number of clients on the difference between EEEW and EEEWS is negligible.

VII. CONCLUSION

In this paper, we presented a power consumption model for office networks and applied the model to evaluate performance of EEE and EEW. We also explored the possibility of further conserving power by combining the existing power saving techniques. Our analysis results showed that for the average throughput up to $0.5Mbps$, by combining EEE and EEW we can save more than 66% of the power consumed if using only EEE and it is even more if we put link-sleep technique into the combination.

In the future, we first develop the current model to make it closer to the reality such as applying the exponential distribution for the packet length. 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 develop a simulation based on real traffic to verify the validity of the analysis.

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