An Adaptive Power Saving Mechanism in IEEE 802.11 Networks to Support IP Paging Protocol

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Abstract

Terminal paging is a procedure to locate a called mobile host (MH), which registered only approximated location information. The paging aims to reduce signalling overhead and power consumption in the MH. Recently, IP paging protocol has been widely designed for the terminal paging in IP-based mobile networks. However, since any power save mechanism is not supported in IP layer by itself, it is difficult to obtain the optimized power consumption effects. In other words, IP paging protocol should be cooperated with the power save mechanism supported in link layers. In this paper, we propose a new power saving mechanism in IEEE 802.11 networks in order to efficiently integrate with IP paging protocol. Unlike the existing power saving mechanism, the proposed power saving mechanism adaptively adjusts the wake-up interval by estimating the future idle time of MH based on the previous patterns. In terms of performance evaluation, we formulated and compared the total cost, incurred in the IP paging protocol deployed over the power saving mechanism, when the existing scheme, the proposed scheme, and the optimum scheme are used. As a result, the proposed adaptive power saving mechanism is more close to the optimum solution than the current power saving mechanism.

1 Introduction

In wireless/mobile networks, since mobile hosts (MHs) are free to change their attachments to the networks, location management scheme is required to provide MHs with continuous services. The location management scheme is divided into two procedures: *location update* and *terminal paging*. Location update is an operation wherein an MH informs the network of its current location. On the other hand, terminal paging is a procedure that determines the exact location of the MH. In the current cellular networks such as GSM and IS-95, location management is supported by the specialized protocol suite for each network standard. Hence, it is difficult to apply a location management protocol used in a network to another network. Furthermore, the next-generation wireless/mobile networks will be heterogeneous networks that various access networks are incorporated. Therefore, it is necessary to design a unified location management protocol, which can be adapted to any types of wireless access networks. To resolve these problems, IP (Internet Protocol)-based location management schemes were proposed by Internet Engineering Task Force (IETF). In terms of location update, Mobile IP and its variants were proposed and several IP paging protocols [1-3] were proposed to support terminal paging in IP-layer.

The main advantage of the terminal paging is to minimize power consumption of MHs by avoiding frequent location update procedures. However, it is impossible to obtain a suitable power saving gain by a simple state transition in IP layer without any help of power saving mechanisms supported in lower layers. Hence, when IP paging protocol is deployed in the IEEE 802.11 networks, it should be integrated with Power Saving Mode (PSM) supported in the IEEE 802.11 standard. In the IEEE 802.11 PSM, an MH goes to sleep mode when it is not actively sending or receiving data packets. The MH wakes up periodically every fixed time interval (i.e., *wake-up interval*) to check whether there are some packets destining it.

However, the existing IEEE 802.11 PSM with the fixed wake-up interval shows low system performance in terms of power consumption. For example, if the wake-up interval is too small, an MH may wake up too frequently even though there are no packets. On the other hand, too large wake-up interval cannot meet the specified paging delay constraint. In our previous work, we analysed the performance of IP paging protocol deployed in IEEE 802.11 networks using Power Saving Mechanism [4]. In this work, we investigated the impact of the session arrival rate and the wake-up interval on the protocol performance in both the delay-sensitive and the delay-insensitive sessions. The results indicated that it is necessary to find the optimal wake-up interval required to minimize MH's energy consumption, while satisfying the given delay constraints.

Intuitively, the ideal power save mechanism should allow an MH to sleep continuously during all of the idle period and awake the MH just before the arrival of the paging request message. The ideal power save mechanism, however, is not feasible because it is impossible to predict the time when a paging request message will arrive at Paging Agent (PA) [5] in future. Therefore, it is necessary to estimate the length of the idle period in order to find the optimal wake-up interval minimizing power consumption.

Recently, Krashinsky et al. [6] proposed the Bounded Slowdown (BSD) protocol in order to overcome long delay problems occurred when the IEEE 802.11 power saving mechanism is used for Web-like transfers. In the BSD protocol, the wake-up interval is dynamically adapted to network activity. BSD is an optimal solution to the problem of minimizing energy consumption while guaranteeing that a connection's RTT does not increase by more that a factor *p* over its base RTT, where *p* is a protocol parameter that exposes the trade-off between minimizing energy and reducing latency. However, since BSD is designed for Web-like transfers, it is not appropriate to apply BSD for general IP sessions, which may have different traffic characteristics from Web-like transfers.

In this paper, we proposed an adaptive power saving mechanism based on the IEEE 802.11 PSM. In the adaptive PSM, an MH uses a constant, called *adjustment constant*, in order to adjust the wake-up interval during the idle period. The idle period length is estimated by a simple estimation scheme using the previous communication patterns. To determine the adjustment constant, we formulate the wake-up interval selection problem and present its solution.

The remainder of this paper is organized as follows. Section II introduces the power saving mechanism defined in the IEEE 802.11 standard. Section III describes an adaptive power saving mechanism to adjust the wake-up interval during the idle period. In Section IV, we formulate a wake-up cost and a paging delay cost. In addition, we propose a problem to find out the optimal wake-up interval satisfying the given delay constraints. In Section V, we introduce an estimation scheme for the idle period using the previous traffic patterns. Section VI shows simulation results and Section VI finally concludes this paper.

2 IEEE 802. 11 Power Saving Mechanism

In wireless communication, it is preferable to turn MHs to low power consuming power saving (PS) mode, while they are not actively communicating, and wake them up just before when data packets destined for them arrive in the networks. However, since MHs in PS mode cannot know when packets arrive for them, it is impossible to follow this rule exactly. Therefore, there are two problems to be addressed in the case of power saving for MHs:

- How does an MH in PS mode receive packets from other stations?
- How does an MH send to another MH, which is in power save mode?

In IEEE 802.11 PSM, the basic idea is all MHs in PS mode have to be synchronized to wake up at the same time. At this time, a window period starts during which the sender announces that it has buffered frames for the receiver. Any MH that receives such an announcement frame stays awake until the entire frame is delivered.

Specifically, IEEE 802.11 supports two power modes: active and power saving modes. Compared with active mode, an MH in PS mode consumes extremely low power.

The power saving protocols in IEEE 802.11 can be operated in infrastructure mode or ad-hoc mode. The detailed operations of two modes are quite different. Since IP paging protocol operates in infrastructure networks, this section focuses on the power saving protocol in infrastructure mode. In the infrastructure mode, there is an access point (AP) to monitor the mode of each MH. An MH in the active mode is fully powered and thus may send and receive packets at any time.

On the other hand, an MH in the PS mode only wakes up periodically to check whether there are any incoming packets from the AP. An MH always notifies its AP when changing modes. Periodically, the AP transmits beacon frames spaced by a fixed beacon interval (BI). An MH in the PS mode should monitor these frames. Once every beacon interval, which is typically set to 100ms, the AP sends a beacon containing a traffic indication map (TIM), which contains the ID's of those MHs in PS mode for which there are buffered unicast packets waiting in the AP. Upon hearing its ID, an MH in PS mode should stay awake for the remaining beacon interval. During the contention period (i.e., DCF (Distributed Coordination Function)), an awakened PS host can issue a PS-POLL to the AP to retrieve the buffered packets. On the other hand, during the contention-free period (i.e., PCF (Point Coordination Function)), a PS host waits for the AP to poll it. Typically, MHs listen to every beacon, but the MHs can also be configured to skip several beacons between listen times by setting listen interval. Spaced by a fixed number of beacon intervals, the AP will send deliver TIMs (DTIMs) within beacon frames to indicate the presence of buffered broadcast packets. Immediately after the DTIMs, the buffered broadcast packets will be sent. Whenever the AP sends data to an MH, it indicates whether or not there is more data outstanding, and the MH goes to sleep only when it has retrieved all pending data from the AP. If the MH has data to send, it can wake up in order to send the data without waiting for a beacon.

Power saving protocol in ad-hoc mode, where the packet store and forward and the timing synchronization has to be done in a distributed manner, is more complex. Details of the power saving protocol used in ad-hoc networks can be found in [7].

3 Adaptive Power Saving Mechanism

As mentioned above, the adaptive power saving mechanism is based on the IEEE 802.11 PSM. However, in the adaptive PSM, the wake-up interval during the idle period is adjusted as the ρ (adjustment constant) times of beacon interval, which is usually set to 100ms. ρ is an integer value to adjust the length of wake-up interval adaptively. Figure 1 shows a timing diagram in the adaptive power saving mechanism with the adjustment constant of 3. Let *AD* and *ID* be the active duration and the idle duration, respectively. *IS* denotes an inter-session arrival time. *T* is the active timer value to separate data sessions in connectionless IP networks. The operation from the beginning of a session to the expiration of the active timer is same as that of the IEEE 802.11 PSM. In other words, an MH wakes up every beacon interval before the timer expiration. However, the MH determines the optimal adjustment constant (ρ^*) when the idle period begins (at τ_0), and it wakes up only per ρBI during the idle period. If a paging request message is arrived at τ_1, an idle period is ended and the time period from τ_1 to the next wake-up epoch (τ_2) becomes the paging delay (D_p).

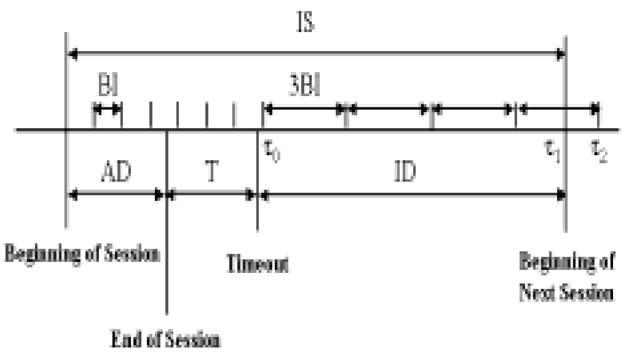

Figure 1 The Timing Diagram in the Adaptive Power Saving Mechanism

4 Problem Formulation

In the adaptive PSM, an MH, which transits to the idle state after the expiration of the active timer, should determine the optimal adjustment constant to minimize its energy consumption. To formulate this selection problem for the wake-up interval, we defined a cost (C_{total}) incurred when IP paging protocol is employed in IEEE 802.11 networks. The cost consists of a wake-up cost ($C_{wake\text{-}up}$) and a paging delay cost (C_{delay}), which are occurred per session arrival.

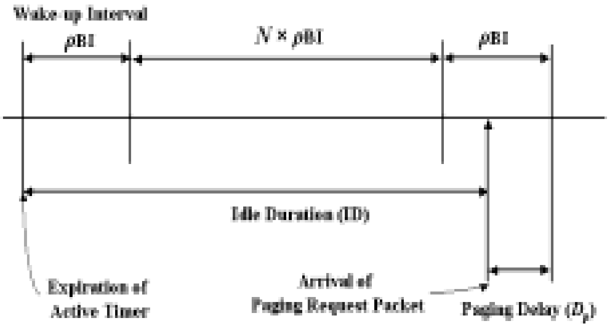

Figure 2 The Arrival Pattern of a Paging Request Packet

4.1 Wake-up Cost

The wake-up cost refers to the cost incurred when an MH wakes up to check whether there are incoming packets in the AP at the beginning of the wake-up interval. When an MH wakes up and remains in active state, it consumes a larger power than in sleep mode. Therefore, the number of wake-ups is associated with the power consumption in MHs. Based on this observation, we define the wake-up cost as a function of the number of wake-ups during the inter-session arrival time. As mentioned above, the wake-up interval during the active duration is the same as the beacon interval. On the other hand, the adjusted wake-up interval used in the idle duration after the expiration of the active timer is ρ times the beacon interval. Thus, the wake-up cost can be expressed as Eq. (1).

$$C_{wakeup} = \left(\left\lfloor \frac{AD + T}{BI} \right\rfloor + \left\lfloor \frac{ID}{\rho BI} \right\rfloor \right) \cdot \alpha \qquad (1)$$

where α is a weighting factor for the wake-up cost. The terms, $\left\lfloor \frac{AD + T}{BI} \right\rfloor$ and $\left\lfloor \frac{ID}{\rho BI} \right\rfloor$, represent the number of wake-ups before the timeout and in the idle duration, respectively.

4.2 Paging Delay Cost

On the other hand, the paging delay cost is incurred by the delayed reception of a paging request message by the MH in PS mode. Thus, the paging delay cost is associated with the arrival time of the paging request packet within a wake-up period. Figure 2 shows the arrival pattern of a paging request message. We assumed that a paging request message uniformly arrives at an AP in the wake-up period of [0, *ρBI*]. In addition, we assume that one-step uniform paging scheme is used in terms of paging scheme. Therefore, in order to locate an MH in a paging area, only one paging procedure is performed. The first term in Eq. (2), represents the paging delay (D_P) and β is a weighting factor for the paging delay cost.

$$C_{delay} = \left(\left\lceil \frac{ID}{\rho BI} \right\rceil \rho BI - ID \right) \cdot \beta \qquad (2)$$

4.3 Session Blocking Probability

In addition to minimizing the total cost, the session blocking probability (P_B), that is a probability that an incoming data session is rejected due to the late reception of the paging request message, should be less than a specific threshold probability value (P_{th}) to guarantee a certain quality of service to mobile users. When the paging delay constraint (D_{const}) is given, the session blocking probability can be obtained under the assumption of the uniform packet arrival pattern as Eq. (3).

$$P_B = \int_0^{\rho \cdot BI - D_{const}} \frac{1}{\rho \cdot BI} dt = \frac{\rho \cdot BI - D_{const}}{\rho \cdot BI} \qquad (3)$$

Intuitively, there is a trade-off relationship between wake-up cost and paging delay cost. Namely, if the wake-up interval increases, the paging delay also increases, but the wake-up cost decreases. In contrast to this case, as the wake-up interval decreases, the paging delay decreases and the wake-up cost increases. Based on the relationship and the defined cost functions, we formulated the optimal wake-up interval selection problem as follows. We assumed that each time duration (*AD*, *T*, and *ID*) is synchronized with the beacon interval of the IEEE 802.11. P_{th} is a threshold paging blocking probability.

$$\text{Minimize} \quad C_{total} = C_{wakeup} + C_{delay}$$

$$\text{Subject} \quad P_B = \frac{\rho \cdot BI - D_{const}}{\rho \cdot BI} \le P_{th}$$

5 Near Optimal Wake-up Interval Selection

It is simple to find the optimal adjustment constant in the problem formulated in the previous section when the idle duration (*ID*) is given. First, using the threshold blocking probability (P_{th}), we can obtain a candidate set of adjustment constants that satisfy the condition $P_B \le P_{th}$. After then, we can find an optimal *ρ*, that minimizes the total cost, by substituting *ρ* in the total cost function with each *ρ* in the candidate set. In the selection problem, since the total cost is a function of *ρ* and *ID*, we should know the length of idle duration of an MH in order to find the optimal wake-up interval. However, it is impossible to determine how long an MH stays in the idle state at the beginning of the idle period. Therefore, we propose a simple estimation scheme for the length of the idle period and a procedure to find near optimal adjustment constant (ρ_n) minimizing the total cost when there is no information about the exact idle period length.

5.1 A Simple Estimation Scheme for Idle Period

The proposed scheme uses the previous communication patterns of the MH in order to estimate the idle period length. Let ID_{init} be an initial estimated length of the idle period. $ID_e(k)$ and $ID(k)$ denote the k_{th} estimated idle period length and the k_{th} measured idle period length, respectively. Using the initial value and the previous idle period lengths, we estimate the length of the current idle period as the below equation, which is based on widely used ***the exponential weighted average algorithm***. ω is a weighting factor ($0<\omega<1$). $E_{k-1}(ID)$ is the average idle period length from 0_{th} to the $(k-1)_{th}$ idle durations.

$$i)\ k = 1,\quad ID_e(1) = ID_{init}$$

$$ii)\ k \ge 2,\quad ID_e(k) = \omega \cdot E_{k-1}(ID) + (1-\omega)\cdot ID(k-1)$$

$$E_{k-1}(ID) = \left(\sum_{i=1}^{k-1} ID(i)\right) / (k-1)$$

5.2 Procedure to Find Near Optimal Wake-up Interval

Using the estimation scheme for the idle period length, we can find a near optimal adjustment constant (ρ_n). Following pseudo-code shows the algorithm to find ρ_n. The weight value (ω) and the initial value (ID_{init}) are given as system parameters. T_{start} and T_{end} are variables to record the start and end of the idle period, respectively

```
Algorithm          FindNearOptimalWakeupInterval (ω, ID_init)
k :=1;
while(true){
  After the active timer expiration {
    T_start:= Current time;
    If(k=1)    ID_e(k):= ID_init;
    elseif(k>2)
      ID_e(k):=ω·E_k-1(ID)+(1-ω)·ID(k-1); }
  Find ρ_n to minimize C(ρ, ID_e(k))
  The MH wakes up every ρ_n·BI interval
  if(Arrival of paging request message){
    T_end := Current time;
    ID(k):=T_end - T_start;
k++; }}
```

This algorithm is implemented in IP layer and invoked when the active timer expires. To estimate the idle period length, a number of prediction schemes can be applied. However, since these schemes should be available in a network interface card with the limited computation capability, the schemes should be simple. The proposed scheme based on the exponential weighted average algorithm does not require any complex operations. Hence, the proposed scheme may be a more appropriate solution than any other prediction schemes in terms of simple implementation.

6 Performance Evaluation

To evaluate the adaptive power saving mechanism, we perform some simulations in terms of total cost and energy consumption. In simulations, we compare our adaptive power saving mechanism with ideal power saving mechanism and current power saving mechanism with the fixed wake-up interval.

6.1 Simulation Environment

To investigate the impact of the adaptive power saving mechanism, we simulate and calculate the total cost and energy consumption of 100 data sessions. In the simulation, we assume that the session arrival process is a Poisson distribution with parameter λ_s. Therefore, the inter-session time (*IS*) follows an Exponential distribution with a mean time of $1/\lambda_s$. In general, the session duration distribution of IP session doesn't follow an Exponential distribution. Therefore, it is assumed that the session duration distribution follows a Pareto distribution with shape parameter *α* and scaling parameter *ε*, which determines the minimum value. This Pareto distribution has a heavy-tailed property reflecting the characteristics of IP sessions. According to previous works [8, 9], it is proved that a data session in wireless networks has similar characteristics to those of a data session in wired networks. This is because mobile users usually use similar types of applications to those in wired Internet (e.g., web browsing, e-mail, and so on). Eq. (4) and (5) show the probability density functions of the inter-session time and the active duration, respectively.

$$f_{IS}(t) = \lambda_s e^{-\lambda_s t} \tag{4}$$

$$f_{AD}(t) = \frac{\alpha}{\varepsilon}\left(\frac{\varepsilon}{t}\right)^{\alpha+1} \tag{5}$$

In terms of the distribution of the active duration, *α* and *ε* are set to 0.78 and 5.0, respectively, based on the reference values in [8].

6.2 Simulation Results

6.2.1 Cost Comparison

In this paper, we used the exponential weighted average scheme to estimate the idle period length. To predict the idle period length more correctly, the initial value and the weight value should be carefully determined. In addition, sufficient previous patterns are required. In this result, the initial idle period length is assumed to 100ms to avoid unnecessary paging delay. In terms of weight value, a set of weight values (i.e., 0.8, 0.6, 0.4, and 0.2) is evaluated. The session arrival rate and the active timer are set to 10/hour and 0.005 hour, respectively.

We compared our adaptive power saving mechanism (A) with three different power saving mechanisms.

- *Fixed scheme (F)*: This scheme is based on the current IEEE 802.11 PSM with a fixed wake-up interval. The default wake-up interval is 100ms, which is same as beacon interval.
- *Power optimal scheme (P)*: This scheme is object to minimize power consumption, but does not consider

any paging delay constraint. Namely, in this scheme, an MH remains in sleep mode as long as possible without any intermediate wake-ups.

- *Ideal scheme (I)*: This scheme is an optimal power saving mechanism to minimize power consumption while meeting paging delay constraint. Unlike power optimal scheme, an MH often wakes up in order to meet paging delay constraint. To do this, the wake-up interval in this scheme is set to $\min\{\lfloor ID \rfloor, D_{const}\}$.

Since P and I assume that an MH knows the idle period length before entering the PS mode in advance, they cannot be supported in real environment.

Figure 3 shows the variation of the wake-up cost and paging delay cost in each scheme. In this simulation, the weight values, α and β are 0.01, respectively. In addition, the paging delay constraint is set to 1sec. In Figure 3, A1, A2, A3, and A4 represent the adaptive power saving mechanisms with ω of 0.2, 0.4, 0.6, and 0.8, respectively.

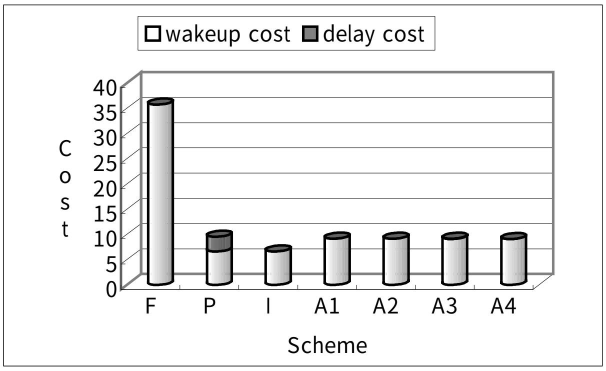

Figure 3 Total Cost Comparison in Different Power Saving Mechanisms

For the cost comparison, we defined a performance parameter named *cost gain* (G_X). The cost gain for X scheme is defined as follows:

$$G_X = \frac{\text{The cost of X scheme}}{\text{The cost of ideal scheme}}$$

In terms of wake-up cost, P and I show the lowest cost among various power saving mechanisms. However, F, which is currently used in the IEEE 802.11 standard, shows the highest wakeup cost. Specifically, the cost gain of F is 5.4. On the other hand, the cost gains of adaptive power saving schemes (A1-A4) are about 1.39. In other words, when the adaptive power saving mechanism is used, the wake-up cost can be reduced to about 25.7% of the current power saving mechanisms.

In terms of weight value in the exponential weighted average scheme, the wake-up cost is minimum when the weight value is 0.2 (A4). Namely, a smaller weight value is more appropriate to estimate the idle period length than larger values. A smaller weight value means that the weight of the recent value is higher than that of the aggregated average value. However, the differences among adaptive power saving mechanisms with different weight values are not high. This is because, in most cases, the wake-up interval in the adaptive scheme is affected by the maximum wake-up interval meeting the threshold blocking probability rather than the estimated idle period length.

In terms of paging delay cost, P shows the highest paging delay cost. As mentioned above, this is because P dose not consider any delay constraint so that P sleeps as long as possible during the idle duration. In contrast, in the fixed power saving mechanism, since an MH wakes up every 100ms, the paging delay cost is very small and the paging delay cost gain is almost 1.0. (Note that delay constraint used in the simulation is 1sec, which is larger than 100ms.) The paging delay cost gain of adaptive scheme is about 10.48. The paging delay cost gain is relatively higher than the wake-up cost gain. Of course, the paging delay cost is dependent the delay constraint and the threshold blocking probability used.

Total cost gains of the adaptive schemes are about 1.40. In contrast, the total cost gains of F and P are 5.42 and 1.44, respectively. Although P outperforms A in terms of wake-up cost, P requires tremendous the paging delay cost so that the total cost of A is smaller than P.

6.2.2 Energy Consumption

In addition to cost comparison, we analyze energy consumption in each power saving scheme. We use a power consumption model used in [11] in order to calculate energy consumption by the state transition of an MH in IEEE 802.11 networks supporting IP paging. The active state refers to a state that an MH actively sends or receives some packets. As shown in Table 1, the MH in the active state consumes 1.5W. In the standby state, an MH does not send/receive any packets but it remains awaken state so that the MH consumes 1.15W less than 1.5W in the active state. On the other hand, an MH in the sleep state wakes up only every 100ms to receive beacon from an AP. Thus, an MH in the sleep state consumes an extremely less energy, 0.045W. In IEEE 802.11 PSM, an MH in PS state must stay awake for a period of time (TIM of DTIM) after each beacon. This time period is typically set to 5ms.

Table 1 Power Consumption Model

State	Power consumption (W)
Active (Send/Receive)	1.5
Standby	1.15
Sleep	0.045

Figure 4 shows the energy consumption in each power saving scheme as the session sequence number increases. It is assumed that the initial energy of an MH is 1000J. After 1000 sessions, the remaining energies of F, P and I are 878.23J, 894.33J, and 894.31J, respectively. Since an MH wakes up periodically even though during a long idle period in the fixed power saving scheme, it wastes a lot of energy due to frequent wake-ups. On the other hand, in P, an MH stays in the sleep state as long as possible so that the remaining energy is the highest among various power saving schemes. In the ideal scheme, since an MH often wakes up not to violate the delay constraint, it consumes more energy than power optimal scheme. However, the difference between P and I is small.

The remaining energy consumption in the adaptive power saving scheme is about 892.87J. In other words, the adaptive scheme consumes more energy than P and I by

1.45J, but it consumes less energy than F by 14.64J. In short, the adaptive power saving mechanisms outperform fixed power saving mechanisms in terms of energy consumption.

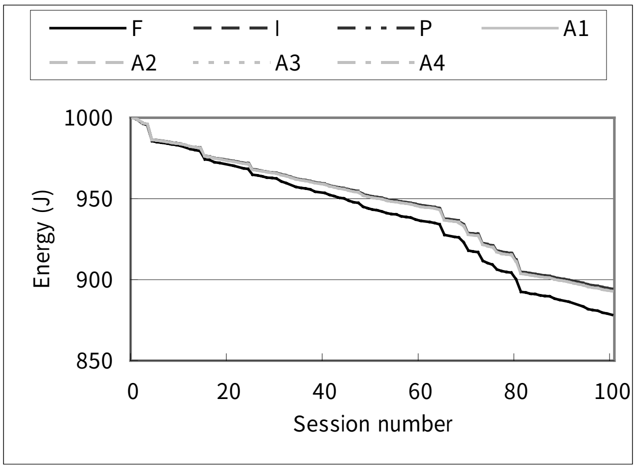

Figure 4 Energy Consumption in Different Power Saving Mechanisms

7 Conclusion

In this paper, we proposed an adaptive power saving mechanism to support IP paging in the IEEE 802.11 networks. As a result of simulation, the adaptive power saving mechanism can reduce the energy consumption by 12%. In addition, the adaptive scheme outperforms the fixed scheme in terms of the total cost, which consists of the wake-up cost and the paging delay cost.

The key scheme in order to reduce the energy consumption is how to estimate the idle period length. In this paper, we used a simple estimation scheme, called exponentially weighted average scheme. However, the performance of this scheme is highly dependent on the initial estimated value and the weight value. Therefore, we will perform more simulations with different parameter values and analyse their performances. Based on these results, we will investigate the analysis to find the optimal initial value and the weight value.

In addition, to enhance the performance of the estimation scheme, many different schemes are available. Especially, Bayes' theorem [10] is widely used to estimate a value based on the previous values. Hence, in the future work, we will propose an estimation scheme based Bayes' theorem. However, it is required to reduce the computation overhead to apply Bayes' theorem to the implementation in network interface cards. Consequently, we will perform a comparative study of each estimation scheme.

8 Acknowledgements

This work was supported in part by the Brain Korea 21 project of the Ministry of Education and in part by the National Research Laboratory project of the Ministry of Science and Technology, 2003, Korea.

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