On Optimizing Energy Consumption for Mobile Handsets

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***Abstract*—To reduce energy consumption (EC), a mobile handset system can be designed in such a way that while the data-receiving unit in a mobile handset is receiving and monitoring data packets, the rest part of the handset (i.e., a processing unit and a user interface) is switched off into a *sleep mode*. In this paper, we study the timing when the rest part of the handset should wake up. Several schemes (i.e., *Always-ON*, *Always-OFF*, *Wake-up upon Arrival*, *Wake-up upon Full*, and *the fractional threshold scheme*) are studied and compared in terms of energy saving and the packet dropping probability (PDP). We formulate the total EC for all theses schemes analytically. Furthermore, we show how to choose optimal thresholds for *the fractional threshold scheme* for the following two-optimization problems: 1) minimizing the switch-on rate with a bound on the PDP and 2) minimizing the total EC with a bound on the PDP. Our study shows that the fractional threshold scheme is the best scheme. Simulations are carried out to validate analytic models.**

***Index Terms*—Energy consumption, mobile handset, sleep mode, wake-up mechanism.**

I. Introduction

ONE of the critical limiting operational factors for mobile handsets is that their operation time is restricted by the battery capacity, even in stand-alone mode [2]. Therefore, designing the system in an energy consumption (EC)-aware manner is imperative [3], [4], and it is one of the primary objectives in the design of mobile handsets [5]. Significant reduction of battery size and weight can be difficult so that alternative strategies need to be employed toward the goal of energy savings in both communication and networking aspects [5], [6].

Operations of mobile handsets may significantly consume battery energy. The components consuming energy in a mobile handset can be designed in such a way that while the data-receiving unit (DRU), a fixed-size memory queue in the handset for buffering data packets, is receiving and monitoring data packets, the rest part of the handset, a user interface and a processing unit (PU) that processes received data packets, is switched-off into a *sleep mode* [1]. An example of switching-off the user interface is a Motorola Star TAC cellular handset under Sprint PCS, in which, the user interface is switched-off if there is no activity for several seconds. For the remainder of this paper, we refer to the rest part of the handset (the user interface and the PU) as the PU in general. Switch-on actions consume a great amount of energy [7], [8]. Immediately waking up upon receipt of a packet may cause too many switch-on actions, thus consuming more battery energy and degrading the power efficiency. Waiting for more packet arrivals before performing a switch-on action avoids many switch-on actions, but causes packet losses due to a limited buffer size. Therefore, there is a tradeoff between energy saving and the number of packets dropped. In [1], an integer threshold-based scheme was proposed in which waking-up happens when the number of packets in the buffer reaches a fixed threshold, and the switch-on rate (SOR) was studied. However, neither the total EC nor optimizing the total EC was studied. In this paper, we consider the influence of the buffer size of the DRU on the actions of switching on/off the PU to reduce EC for mobile handsets. We study several *wake-up* mechanisms, and formulize the total EC analytically for each mechanism. We study and compare the following schemes:

- *Always-ON (AON)*: the PU is always in the *wake-up mode*.
- *Always-OFF (AOFF)*: the PU is always in the *sleep mode*. *AOFF* is considered for comparison purpose.
- *Wake-up upon arrival (WA)*: whenever there is a packet arrival, the PU wakes up, and whenever there is not any packet in the buffer, the PU goes to sleep.
- *Wake-up upon full (WF)*: whenever the buffer is full, the PU wakes up, and whenever there is not any packet in the buffer, the PU goes to sleep.
- *Fractional threshold method*: we propose a fractional threshold *wake-up* mechanism in which the switch-on action is performed with a probability when the number of packets in the buffer of the DRU reaches a threshold. Whenever there is no packet, the PU goes to sleep. Such an approach improves the integer threshold approach by allowing the threshold to be a random variable so that the threshold is no longer a fixed deterministic integer value, but an integral random variable with a probability distribution. The mean of this variable can be regarded as the nominal threshold value, above which waking-up happens. The nominal threshold value can be a non-negative real number rather than an integer. Therefore, the fractional scheme provides a finer grained threshold value.

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The fractional threshold concept has been adopted in wireless/mobile networks for different problems. For example, the well-known Fractional Guard Channel scheme is the optimal approach for channel assignments, and it outperforms the Guard Channel approach [12], [13]. Fractional movement-based location area update scheme [14] outperforms the normal location area update scheme. In this paper, the fractional concept has been applied to save EC in mobile handsets, and the following two optimization problems are studied: 1) minimizing the SOR with a bound on the packet dropping probability (PDP) and 2) minimizing the total EC with a bound on the PDP.

The rest of this paper is organized as follows. Wake-up schemes are presented in Section II. Section III provides analytic models and formulation for all these schemes. Section IV provides optimality analysis and a method to find optimal fractional thresholds. Performance evaluations are reported in Section V. Section VI concludes this paper.

II. Wake-Up Schemes

In this section, we present several wake-up schemes as follows. We present the fractional threshold scheme in Section II-A and other schemes in Section II-B.

A. Fractional Threshold Scheme

The fractional threshold scheme allows the threshold to be random. Therefore, the threshold is no longer a fixed deterministic integer value, but an integral random variable with a probability distribution. The mean of this probability distribution can be treated as the nominal threshold value, above which the PU will be switched on, and this nominal threshold can be a nonnegative real number instead of an integer.

Specifically, in a mobile handset system with the fractional threshold scheme, when the packet-receiving queue is empty, the PU is switched off into the sleep mode; it is switched on to the wake-up mode with probability $(1-\alpha)$ when the number of packets in the queue reaches t; otherwise it is switched on when the number of packets in the queue reaches $t+1$. The fractional threshold algorithm is shown in Table I.

Definition: The Threshold Random Variable ($\mathbf{X_t}$): for any fixed threshold t, the threshold for the fractional threshold scheme is a random variable $\mathbf{X_t}$, with a probability density function (pdf) defined as follows:

$$f(\mathbf{X}_t) = \begin{cases} 1-\alpha & \text{if } \mathbf{X}_t = t \\ \alpha, & \text{if } \mathbf{X}_t = t+1 \\ 0 & \text{otherwise.} \end{cases} \qquad (1)$$

where $t = 0, \ldots, N$, $\alpha \in [0,1]$, and N is the buffer size.

Note that in both the description and Table I, we adopt conditional probability, i.e., "otherwise" means the condition that at the threshold t, switch-on action does not happen, whereas in (1), we do not adopt conditional probability. We can prove they are equivalent as follows. From the fractional threshold algorithm listed in Table I, we have $P(\mathrm{X}_t = t) = (1-\alpha)$, and

$$P(\mathbf{X_t}=t+1)=P(\mathbf{X_t} \neq t)=1-P(\mathbf{X_t}=t)=1-(1-\alpha)=\alpha.$$

TABLE I
Fractional Threshold Algorithm

```
// For the Data Receiving Unit (DRU)
//rand (0,1) returns a uniformly random number in the interval [0,1]
While (1)
{ if (a packet arrives){
     if (Num==N) Drop the packet;
     else{Put the packet into the queue; Num++;}
     if(PU in the sleep mode){
       If(Num==t && rand(0,1) ≤(1-α))
           {Switch on PU to the wake-up mode;}
       elseif (Num==t+1)
           {Switch on PU to the wake-up mode.}
     }}}
//For PU in the wake-up mode
while (Num!=0) { Process one packet; Num--;}
Switch off PU to the sleep mode;
```

This proves that our fractional threshold algorithm in Table I conforms to our definition of the fractional threshold pdf in (1). The mean of $\mathbf{X_t}$ is

$$\begin{aligned} E(X_t) &= tP(t) + (t+1)P(t+1) \\ &= t(1-\alpha) + (t+1)\alpha \\ &= t+\alpha. \end{aligned} \qquad (2)$$

The above mean could be any nonnegative real number in the interval $(t, t+1)$ instead of an integer t or $t+1$. The fractional threshold takes on real values from $[0, N]$. We will further discuss the optimality aspect in Section IV.

All mobile handsets run the same algorithm (shown in Table I) in a distributed manner with different optimal thresholds calculated based on both the proposed method and the measured packet arrival rates. How the proposed approach is dynamically adjusted according to different traffic conditions is discussed in Section IV-C.

B. AON, AOFF, WA, and WF

In the AON scheme, the PU is always in the wake-up mode. In the AOFF scheme, the PU is always in the *sleep mode*. In AON, the energy saving is the worst, but the PDP is the smallest. In AOFF, the energy saving is the best, but the PDP is the worst, i.e., one. AOFF is a nonworking case. AON and AOFF are two extreme cases in terms of energy saving and the PDP.

In WA scheme, whenever there is a packet arrival, the PU wakes up, and whenever there is not any packet, the PU goes to sleep. In WF scheme, whenever the buffer is full, the PU wakes up; and whenever there is not any packet, the PU goes to sleep. WA and WF are special cases of the fractional threshold scheme.

III. Analytical Models

Assume that the buffer size of the DRU is N in terms of packets. More specifically, the buffer can hold up to N packets exactly. We further assume that the packet arrivals to a handset follow a Poisson distribution with rate λ. The service time for processing packets follows an exponential distribution with rate μ. Moreover, the two distributions are independent of each other. Therefore, the handset PU can be modeled with a Markovian process with finite capacity [9], [10]. According

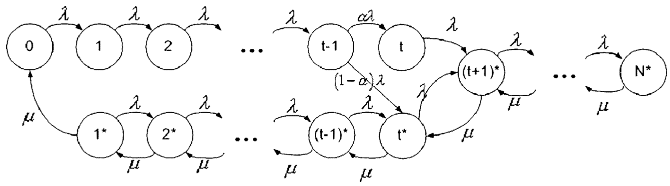

Fig. 1. State transition diagram for the fractional threshold scheme.

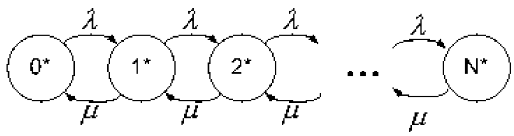

Fig. 2. State transition diagram for the *AON* scheme.

to these assumptions, we will derive analytic models for all wake-up schemes.

To model the fractional threshold scheme, we must distinguish two modes: the sleep mode in which packets are being received while the PU is switched-off, and the wake-up mode in which packets are being received while the PU is processing the packets. In the fractional threshold scheme, the PU is switched off into the sleep mode when the buffer is empty. It is switched to the wake-up mode with probability $(1-\alpha)$ when the number of packets in the buffer reaches t, and is switched to the wake-up mode with probability α when the number of packets in the buffer reaches $t+1$. In other words, when the number of packets accumulated in the buffer reaches t, a switch-on action is performed with probability $(1-\alpha)$. Otherwise, a switch-on action is performed when the number of packets accumulated in the buffer reaches $t+1$. The state transition diagram for the fractional threshold scheme is shown in Fig. 1, where, state (i), $(0 \le i \le t)$ indicates that the queue has i packets, and the PU is in the *sleep mode*. State (j^*), $(1 \le j \le N)$ indicates that the queue has j packets and the PU is in the wake-up. It is also shown in Fig. 1 that when the queue is empty [state (0)], the PU is switched off into the sleep mode. When the queue is in state $(t-1)$, the next state becomes either state (t^*) (the wake-up mode), or state (t) (the sleep mode). When the queue is in state (t), the next state is switched on into the wake-up mode [state $((t+1)^*)$].

From [9] and Fig. 1, we can easily derive the instantaneous transition probabilities from state $(t-1)$ to either state (t) or state (t^*) as follows. Note that t and α are fixed number here.

$$P_{t-1,t^*} = \frac{(1-\alpha)\lambda}{(1-\alpha)\lambda + \alpha\lambda} = (1-\alpha) \quad (3)$$

$$P_{t-1,t} = \frac{\alpha\lambda}{(1-\alpha)\lambda + \alpha\lambda} = \alpha. \quad (4)$$

Therefore, when the queue is in state $(t-1)$, the next state is switched on into the wake-up mode with probability $(1-\alpha)$ and stays in the sleep mode with probability α. In other words, when the number of packets in the queue reaches t, the PU is switched on to the wake-up mode with probability $(1-\alpha)$, and stays in the sleep mode with probability α.

In AON scheme, the PU is always in the wake-up mode. AON is a special case of the fractional threshold scheme when $\alpha = 0$ and $t = 0$, in which Fig. 1 is changed into Fig. 2. In the AOFF scheme, the PU is always in the sleep mode. AOFF is a special case of the fractional threshold scheme when $\alpha = 0$ and $t > N$, in which, Fig. 1 is changed equivalently into Fig. 3. In WA scheme, whenever there is a packet arrival, the PU wakes up, and whenever there is not any packet, the PU goes to sleep. WA is a special case of the fractional threshold scheme when $\alpha = 0$ and $t = 1$, in which, Fig. 1 is changed into Fig. 4, and the only state in the sleep mode is the state (0). In WF the scheme, whenever the buffer is full, the PU wakes up; whenever there is not any packet, the PU goes to sleep. WF is a special case of the fractional threshold scheme when $\alpha = 0$ and $t = N$, in which, Fig. 1 is changed into Fig. 5.

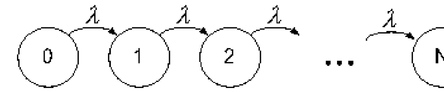

Fig. 3. State transition diagram for the *AOFF* scheme.

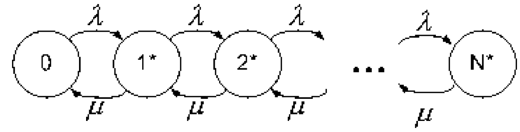

Fig. 4. State transition diagram for the *WA* scheme.

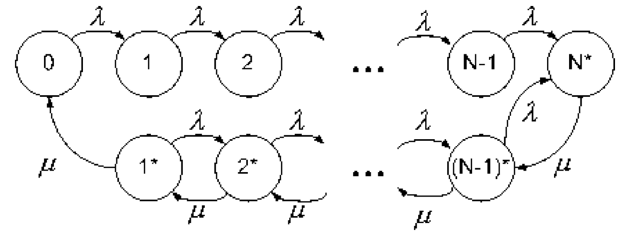

Fig. 5. State transition diagram for the *WF* scheme.

Based on the state transition diagrams in Figs. 1–5, equilibrium equations can be used to derive stationary probabilities for each scheme. Since all the schemes are special cases of the fractional threshold scheme, next we first study the fractional threshold scheme.

For the fractional threshold scheme, based on the state transition diagram in Fig. 1, the following equilibrium equations hold when the PU is in a steady state, where P_i denotes the stationary probability of state (i).

$$\begin{aligned}
&\text{States} && \text{Rate enters states} = \text{Rate leaves states} \\
&0, && \mu P_{1^*} = \lambda P_0 \quad (5)\\
&1 \le i \le t-2, && \lambda P_{(i-1)} = \lambda P_i \quad (6)\\
&t-1, && \lambda P_{t-2} = \alpha\lambda P_{t-1} \\
& && +(1-\alpha)\lambda P_{t-1} = \lambda P_{t-1} \quad (7)\\
&t, && \alpha\lambda P_{(t-1)} = \lambda P_t \quad (8)\\
&(t+2)^* \le i^* < N^*, && \lambda P_{(i-1)^*} + \mu P_{(i+1)^*} = (\lambda+\mu) P_{i^*} \quad (9)\\
&N^*, && \lambda P_{(N-1)^*} = \mu P_{N^*} \quad (10)\\
&1^*, && \mu P_{2^*} = (\mu+\lambda) P_{1^*} \quad (11)\\
&2^* \le i^* \le (t-1)^*, && \lambda P_{(i-1)^*} + \mu P_{(i+1)^*} = (\lambda+\mu) P_{i^*} \quad (12)\\
&t^*, && \lambda P^*_{(t-1)} + (1-\alpha)\lambda P_{t-1} + \mu P_{(t+1)^*} = (\mu+\lambda) P_{t^*} \quad (13)\\
&(t+1)^*, && \lambda P_t + \lambda P_{t^*} + \mu P_{(t+2)^*} = (\mu+\lambda) P_{(t+1)^*}. \quad (14)
\end{aligned}$$

Furthermore, we have

$$\sum_{i=0}^{t} P_i + \sum_{i=1}^{N} P_{i^*} = 1. \tag{15}$$

With (5)∼(15), we can derive the stationary probability for each state. Let $A = \alpha + \rho(1-\rho^t)/(1-\rho)$, $C = \rho(1-\rho^{t-N})$, $B = t + \alpha(1-\rho) - (\rho^2(1-\rho^t)/(1-\rho))$, and $\rho = \lambda/\mu$. With some algebra operations, we can obtain the following equations that are proved in Appendix :

$$P_{N^*} = \frac{A(1-\rho)}{B\rho^{t-N} - CA} \tag{16}$$

$$P_0 = \frac{1-\rho}{B - CA\rho^{N-t}}. \tag{17}$$

Let $F_{\text{switch-on}}(t,\alpha)$ and $\text{PDP}(t,\alpha)$ denote the SOR and the PDP, respectively. They are functions of (t, α). Intuitively, in the long run, the portion of time that the PU stays in the state $(t-1)$ is P_{t-1}. During this time period, the number of arrivals should be the product of the arrival rate and the time period, i.e., λP_{t-1}. Similarly, the portion of time that the PU stays in state (t) is P_t. During this time period, the number of arrivals should be the product of the arrival rate and the time period, i.e., λP_t. Moreover, among the arrivals of λP_{t-1}, only $(1-\alpha)$ portion is switched on. Therefore, also from (8), the SOR will be

$$\begin{aligned} F_{\text{switch-on}}(t,\alpha) &= (1-\alpha)\lambda P_{t-1} + \lambda P_t \\ &= (1-\alpha)\lambda P_{t-1} + \alpha\lambda P_{t-1} \\ &= \lambda P_{t-1} = \lambda P_0 = \frac{\lambda(1-\rho)}{B - CA\rho^{N-t}}. \end{aligned} \tag{18}$$

Intuitively, the SOR will be the same as the switch-off rate in the long run. This fact can be easily proved by formulae (6)–(7) as follows:

$$\begin{aligned} F_{\text{switch-off}}(t,\alpha) &= \mu P_{1^*} = \lambda P_0 = \cdots = \lambda P_{t-1} \\ &= F_{\text{switch-on}}(t,\alpha). \end{aligned} \tag{19}$$

Packets will be dropped when the buffer is full, i.e., when the PU is in state (N^*). Therefore, the $\text{PDP}(t,\alpha)$ is calculated as

$$\text{PDP}(t,\alpha) = P_{N^*} = \frac{A(1-\rho)}{B\rho^{t-N} - CA}. \tag{20}$$

Let E_S and E_W denote ECs of the sleep mode and the wake-up mode, respectively, per unit time, where $E_W > E_S$. Let $E_{S-\text{ON}}$ and $E_{S-\text{OFF}}$ denote ECs of the switch-on action and the switch-off action, respectively, per time. The SOR is measured in terms of the times of switch-on per unit time. Let P_S denote the probability of the PU in the sleep mode. We have

$$P_S = \sum_{i=0}^{t} P_i = (t+\alpha)P_0. \tag{21}$$

TABLE II
THE BINARY SEARCH ALGORITHM

```
/* Return t+α */
double resolution=0.01;
double left=0.0; right=N;
double r=(left+right)/2.0;
if(PDP(N)≤PDP_qos) return N;
while(right-left>resolution){
  if (PDP(r)≤PDP_qos) {
     left=r;
     r=(left+right)/2.0;
  }else {
     right=r;
     r=(left+right)/2.0;
}}
return r;
```

The total EC E_{total} is defined as

$$\begin{aligned} E_{\text{total}} &= E_S P_S + E_W(1-P_S) + E_{S-\text{ON}} F_{\text{switch-on}}(t,\alpha) \\ &\quad + E_{S-\text{OFF}} F_{\text{switch-off}}(t,\alpha) \\ &= E_W - (E_W - E_S)P_S \\ &\quad + (E_{S-\text{ON}} + E_{S-\text{OFF}}) F_{\text{switch-on}}(t,\alpha). \end{aligned} \tag{22}$$

From (18), (20), and (22) for the fractional threshold scheme, we can derive corresponding equations for other special cases of schemes. For AON, AOFF, WA, and WF, we have

$$F_{\text{switch-on}}{}^{\text{AON}} = F_{\text{switch-on}}(0,0) \tag{23}$$
$$\text{PDP}^{\text{AON}} = \text{PDP}(0,0) \tag{24}$$
$$E_{\text{total}}{}^{\text{AON}} = E_{\text{total}}|_{t=0,\alpha=0} \tag{25}$$
$$F_{\text{switch-on}}{}^{\text{AOFF}} = 0 \tag{26}$$
$$\text{PDP}^{\text{AOFF}} = 1 \tag{27}$$
$$E_{\text{total}}{}^{\text{AOFF}} = E_S \tag{28}$$
$$F_{\text{switch-on}}{}^{WA} = F_{\text{switch-on}}(1,0) \tag{29}$$
$$\text{PDP}^{WA} = \text{PDP}(1,0) \tag{30}$$
$$E_{\text{total}}{}^{WA} = E_{\text{total}}|_{t=1,\alpha=0} \tag{31}$$
$$F_{\text{switch-on}}{}^{WF} = F_{\text{switch-on}}(N,0) \tag{32}$$
$$\text{PDP}^{WF} = \text{PDP}(N,0) \tag{33}$$
$$E_{\text{total}}{}^{WF} = E_{\text{total}}|_{t=N,\alpha=0}. \tag{34}$$

IV. OPTIMALITY ANALYSIS AND A METHOD TO FIND OPTIMAL THRESHOLDS

In this section, we study optimality problems for the fractional threshold scheme. In Section IV-A, we first provide some features of the performance metrics; in Section IV-B, we show how to choose the optimal thresholds for the following two problems: 1) minimizing the SOR with a bound on the PDP and 2) minimizing the total EC with a bound on the PDP. Finally, Section IV-C provides some comments on implementation issues for the optimal fractional threshold scheme.

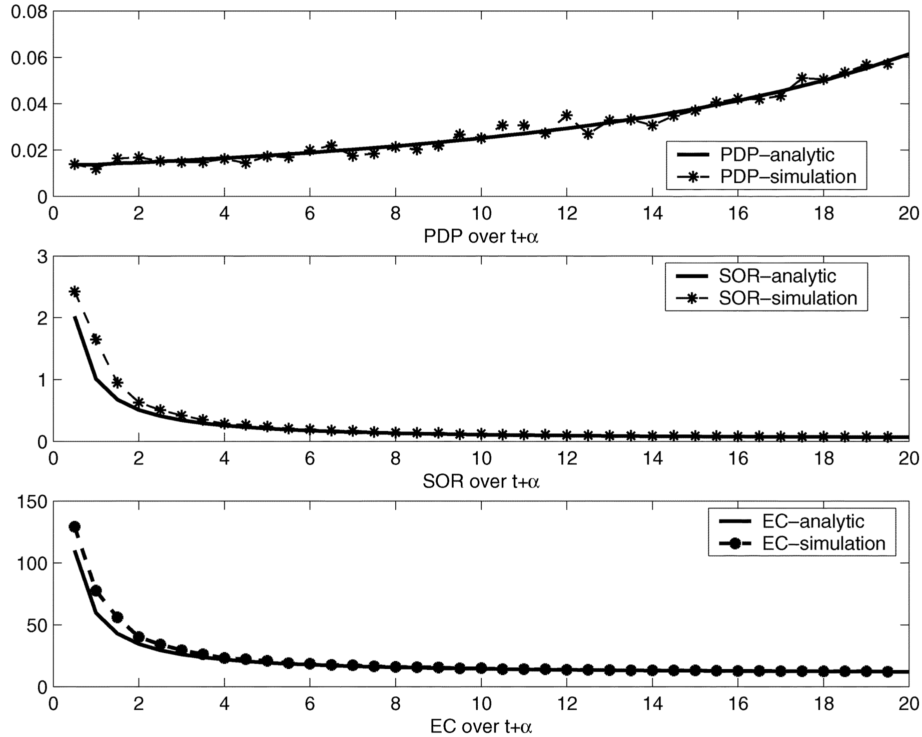

Fig. 6. PDP, SOR, and EC over $t + \alpha(\rho = 0.9)$.

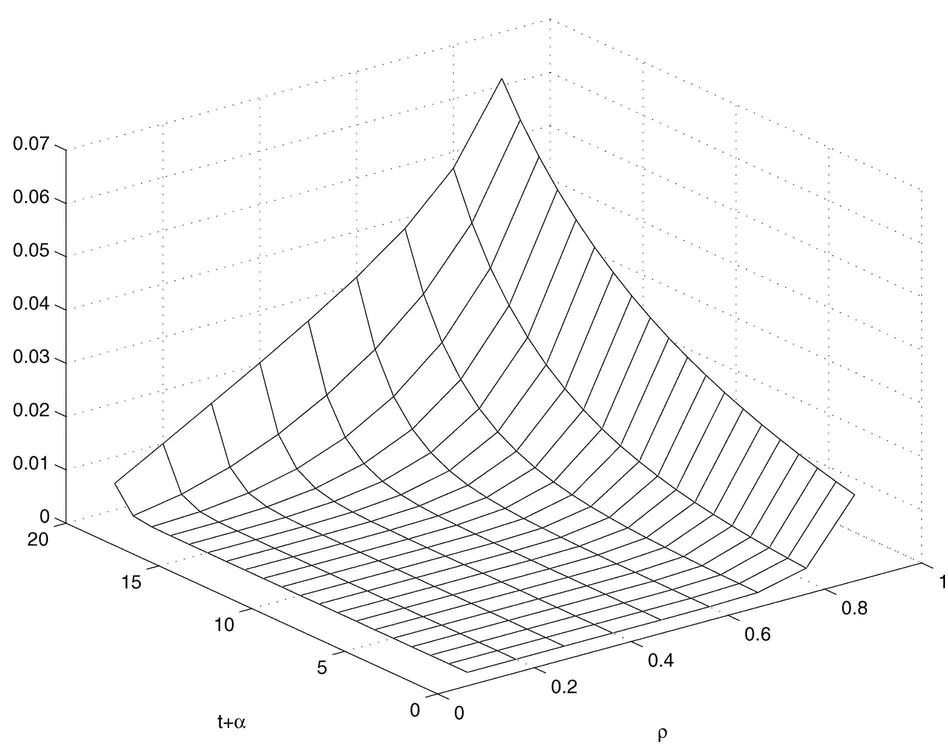

Fig. 7. PDP over ρ and $t + \alpha$.

A. Features of the Performance Metrics

In this section, we study some features of the total EC, the SOR, and the packet-dropping probability for the fractional threshold scheme.

Since $F_{\text{switch-on}}(t, \alpha)$ is a function of t and α, where t and α are the integer and fraction parts of $t + \alpha$, respectively, we can denote $F_{\text{switch-on}}(t, \alpha)$ with $F_{\text{switch-on}}(t + \alpha)$. Therefore, we use $F_{\text{switch-on}}(t, \alpha)$ and $F_{\text{switch-on}}(t + \alpha)$ interchangeably.

In previous section, for fixed values t and α, we have derived the SOR and the PDP. Intuitively, when the mean of the fractional threshold random variable $t + \alpha$ increases, the SOR $F_{\text{switch-on}}(t + \alpha)$ will decrease due to fewer switch-on actions, whereas the $\text{PDP}(t + \alpha)$ will increase due to the slower re-

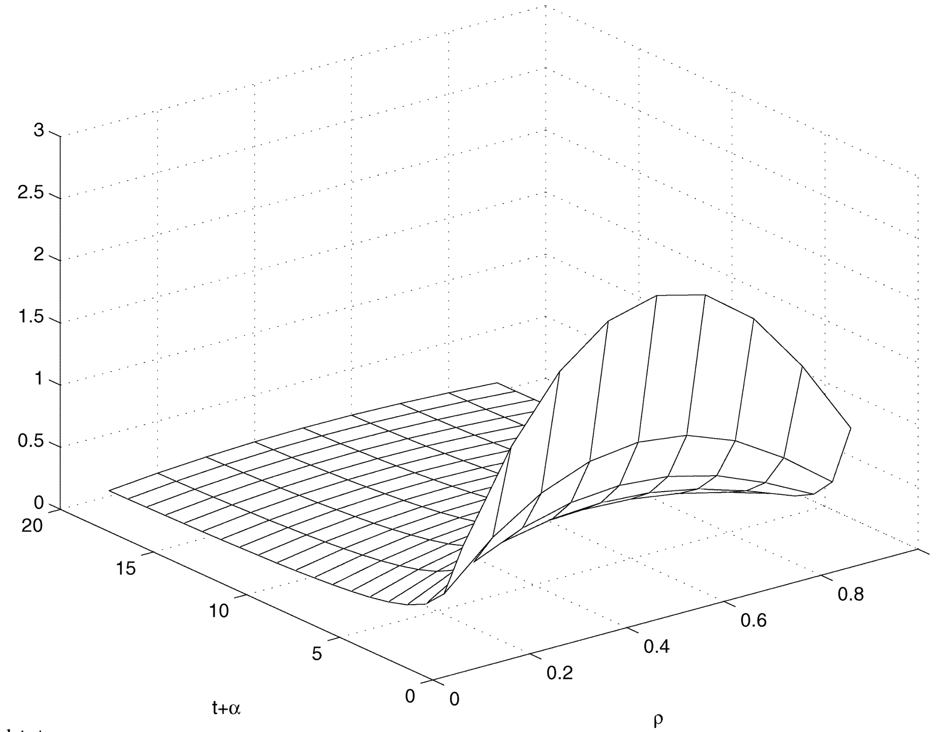

Fig. 8. SOR over ρ and $t+\alpha$.

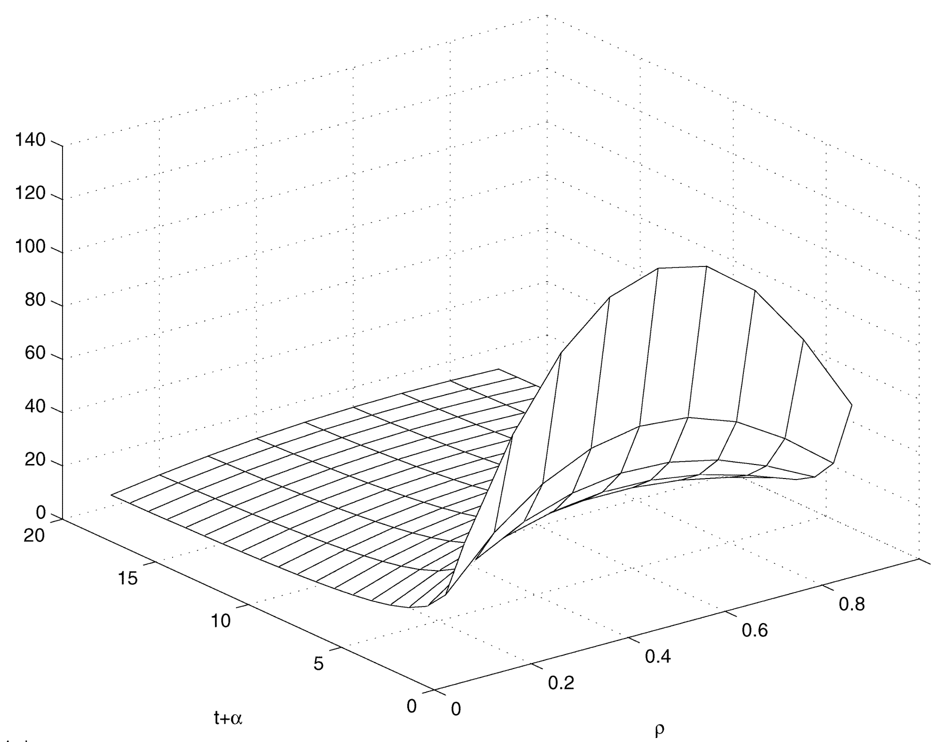

Fig. 9. EC over ρ and $t+\alpha$.

sponses for packet processing. Therefore, we have the following theorem that is proved in Appendix :

Theorem I: or the fractional threshold scheme, if $0<\rho<1$, *the* $\mathrm{PDP}(t,\alpha)$ *is a strictly increasing function of* $t+\alpha$ *and the SOR* $F_{\text{switch-on}}(t,\alpha)$ is a strictly decreasing function. In other words, we have

$$\frac{\partial(\mathrm{PDP}(t,\alpha))}{\partial(t+\alpha)}>0 \tag{35}$$

$$\frac{\partial(F_{\text{switch-on}}(t,\alpha))}{\partial(t+\alpha)}<0. \tag{36}$$

Intuitively, when the mean of the fractional threshold random variable $t+\alpha$ increases, the total EC decreases since: 1) the PU stays more time on the *sleep mode* and 2) there are fewer switch-on actions. Therefore, we can obtain the following theorem that is proved in Appendix .

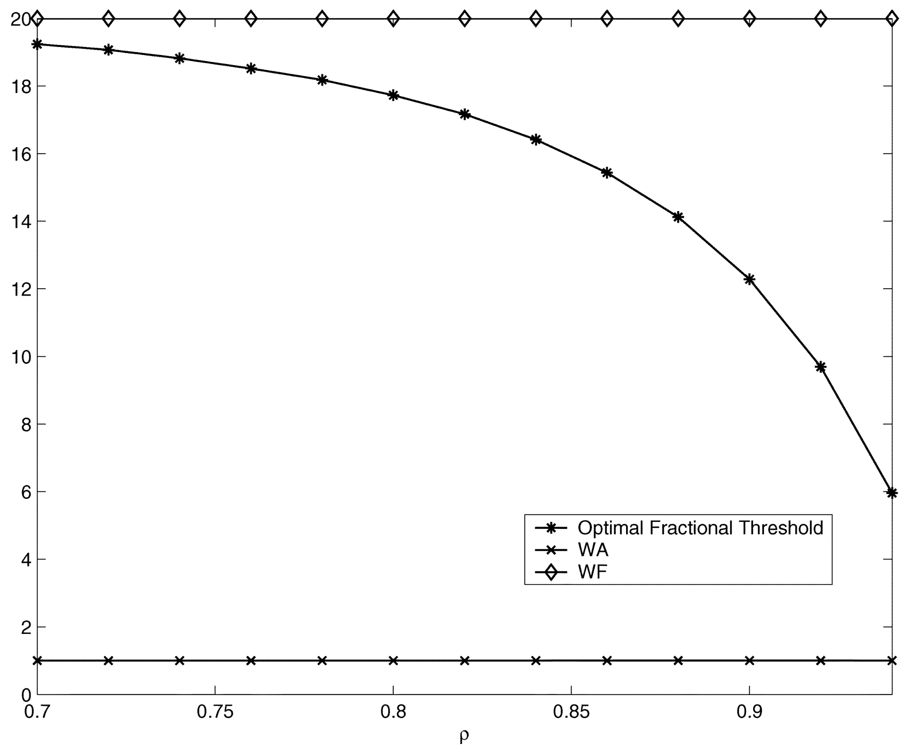

Fig. 10. Thresholds over the traffic load ρ (PDP bound is 3%).

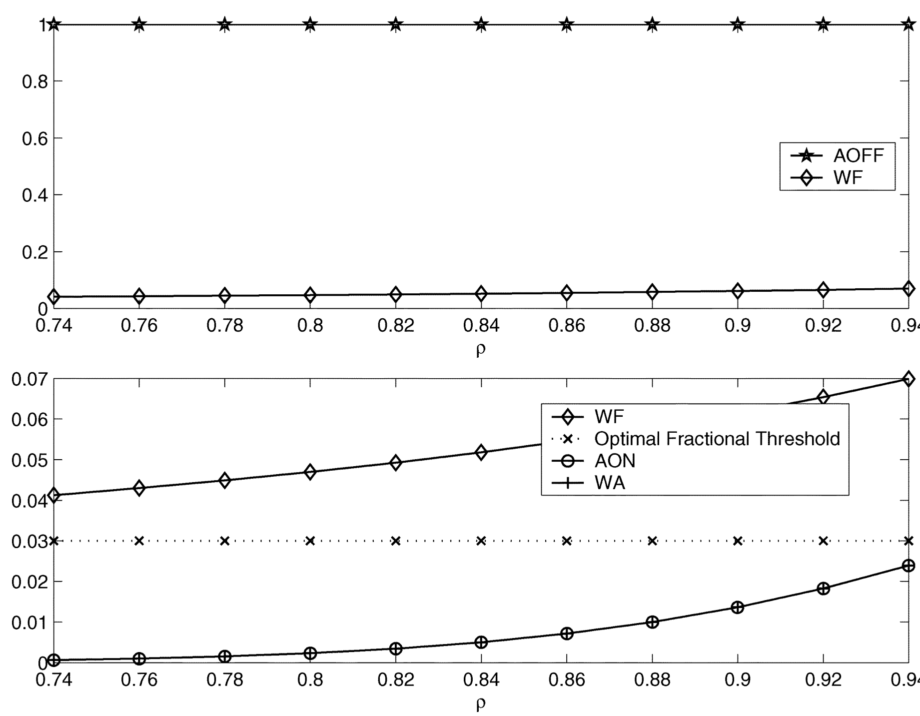

Fig. 11. PDP over the traffic load ρ for different schemes (PDP bound is 3%).

Theorem II: For the fractional threshold scheme, if we have $0 < \rho < 1$, *the total EC,* $E_{\rm total}$ *is a strictly decreasing function of* $t + \alpha$. *In other words, we have*

$$\frac{\partial(E_{\rm total})}{\partial(t+\alpha)} < 0. \tag{37}$$

B. Optimal Thresholds to Minimize the Total Energy Consumption and the SOR

The objective is to find a good pdf in (1) so that the fractional threshold scheme can get better performance. We need to find a 2-tuple *(t, α)*. The domain of the 2-tuple *(t, α)* is

$$D_1 = \left\{(t,\alpha) | t \in D_0 \doteq \{0, 1, \ldots N\}; \alpha \in [0,1]\right\}. \tag{38}$$

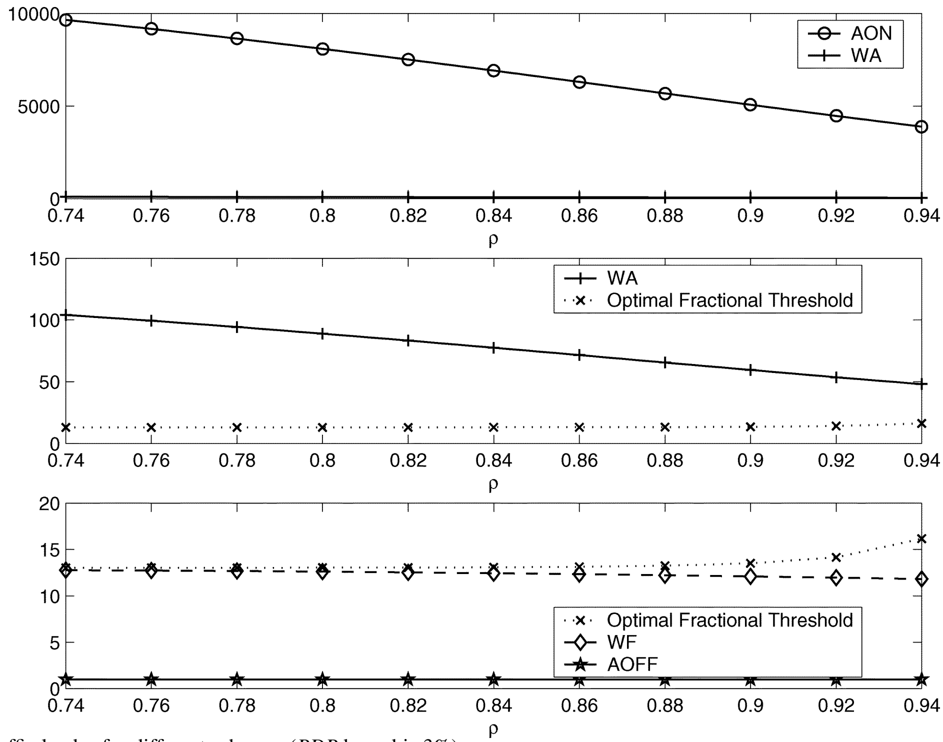

Fig. 12. EC over the traffic load ρ for different schemes (*PDP* bound is 3%).

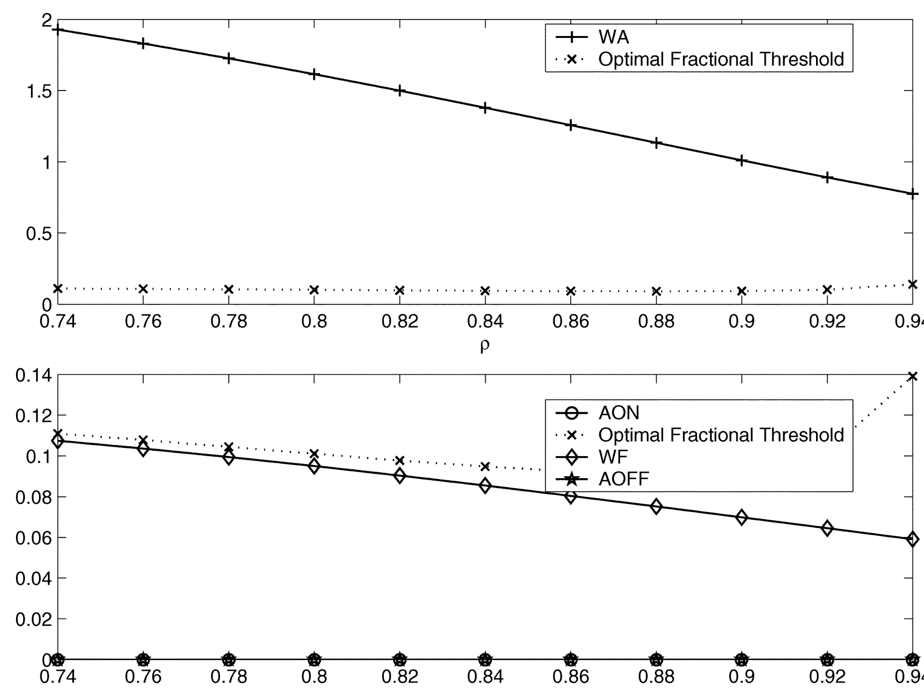

Fig. 13. SOR over the traffic load ρ for different schemes (*PDP* bound is 3%).

Optimization Problem 1 (OP1): For the fractional threshold scheme, denote the SOR and the PDP as $F_{\text{switch-on}}(\boldsymbol{x})$ *and* $\text{PDP}(\boldsymbol{x})$ *respectively, when* $\mathbf{x} = (t, \alpha)$ *and* $(t + \alpha)$ *is used as the fractional threshold. Given that* b *is the predefined PDP bound, find* $\mathbf{x}_{\text{opt}}$*, where* $F_{\text{switch-on}}(\mathbf{x}_{\text{opt}}) = \min_{\mathbf{x} \in D_1}\{F_{\text{switch-on}}(\mathbf{x}) | \text{PDP}(\mathbf{x}) \leq b\}$*, and* $\mathbf{x}_{\text{opt}} \in D_1$.

Optimization Problem 2 (OP2): For the fractional threshold scheme, denote the total EC and the PDP as $E_{\text{total}}(\boldsymbol{x})$ and $\text{PDP}(\boldsymbol{x})$ respectively, when $\mathbf{x} = (t, \alpha)$ and $(t + \alpha)$ is used as the fractional threshold. Given that b is the predefined PDP bound, find $\mathbf{x}_{\text{opt}}$, where $E_{\text{total}}(\mathbf{x}_{\text{opt}}) = \min_{\mathbf{x} \in D_1}\{E_{\text{total}}(\mathbf{x}) | \text{PDP}(\mathbf{x}) \leq b\}$ and $\mathbf{x}_{\text{opt}} \in D_1$.

Lemma 1: Since D_1 *is a closed domain, there must exist optimal solutions of the above two optimization problems.*

Since the total EC is a strictly decreasing function of the fractional threshold, and the PDP is a strictly increasing function of the fractional threshold, the optimal fractional threshold is the maximum fractional threshold under the bound. This is also true

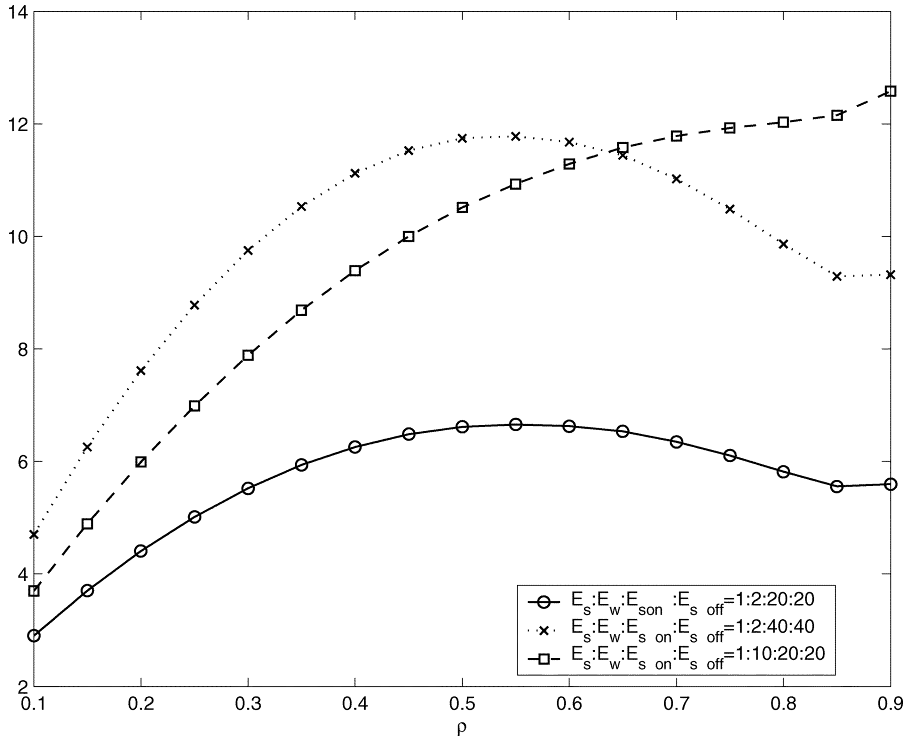

Fig. 14. EC over the traffic load ρ for different ratios of $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}}$ (PDP bound is 3%).

for the optimal fractional threshold for the SOR. Furthermore, the optimal value is unique. Therefore, we have the following Lemma 2 and Lemma 3. We also develop the Binary Search Algorithm, shown in Table II. Lemma 3 holds since the total EC is a strictly decreasing function of the fractional threshold, and the PDP is a strictly increasing function of the fractional threshold.

Lemma 2: The optimal fractional thresholds for OP1 and OP2 are the same and unique.

Lemma 3: The binary search algorithm can find an optimal fractional threshold for OP1 and OP2.

Since t is an integer and α is a fraction between *0* and *1*, we will use $t+\alpha$ and (t, α) interchangeably without causing confusion to represent the nominal threshold. Note that in Table II, we use neither the total EC nor the SOR. There are two approaches of calculating $\mathrm{PDP}(r)$ in Table II. The first approach is to perform a simulation, and measure $\mathrm{PDP}(r)$. The second approach is to calculate P_N. We choose the second approach. Lemma 2, Theorem I, and Theorem II indicate that the binary search algorithm can find an optimal fractional threshold, as stated in Lemma 3. $\mathrm{PDP}_{\mathrm{QoS}}$ is a predefined value of PDP as the QoS requirement.

C. Remarks for Implementation Issues Including Being Dynamically Changed Under Different Traffic Conditions

All the mobile handsets periodically measure traffic conditions for some time and obtain measured packet arrival rate λ; with the measured mean value of traffic load, the algorithm in Table II is used to obtain optimal fractional threshold; finally the algorithm shown in Table I can be run. Whenever traffic conditions are changed, the above procedures are performed repeatedly. Therefore, in case that the traffic load is dynamically changing, the system can measure the traffic dynamically and calculate the optimal fractional threshold dynamically based on the load. To avoid oscillations, window-averaging techniques can be adopted [11].

V. PERFORMANCE EVALUATION

In this section, we study wake-up schemes over various parameters, as well as the two-optimization problems via analytical results and simulation results. Performance metrics include the PDP, the total energy consumption (EC), and the SOR. Parameters include the traffic load $\rho(= \lambda/\mu)$, the fractional threshold $(t + \alpha)$ and the EC ratios $(E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}})$. We adopt $N = 20$. Section IV-A studies performance of the fractional threshold scheme and gives validation with simulations. Section IV-B compares the optimal fractional threshold scheme with other schemes. Section IV-C provides a summary of key results. Note that the optimal fractional threshold scheme is different from the fractional threshold scheme.

A. Performance of the Fractional Threshold Scheme and Validation With Simulations

Fig. 6 shows PDP, SOR, and EC versus the fractional threshold $(t + \alpha)$ for the fractional threshold scheme when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$ and $\rho = 0.9$. As illustrated in this figure, numerical results and simulation results match pretty well. As $t + \alpha$ increases, PDP increases, and both SOR and EC decrease. These observations confirm Theorem I and Theorem II.

Fig. 7 shows PDP for the fractional threshold scheme over the traffic load ρ and the fractional threshold $t+\alpha$. As illustrated in the figure, PDP increases when either the traffic load increases or the threshold increases.

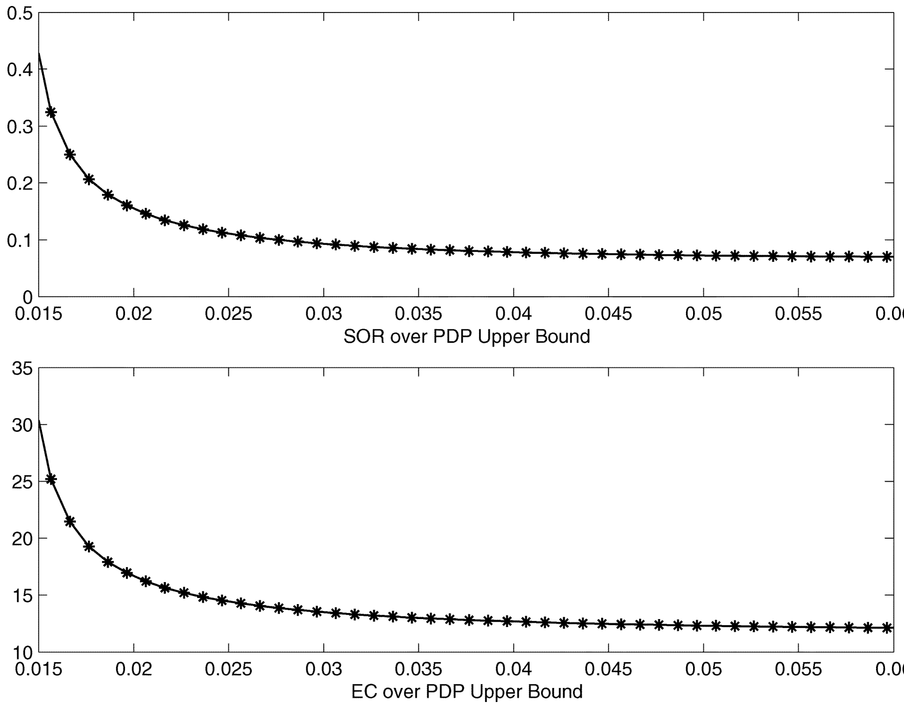

Fig. 15. EC and SOR versus PDP ($E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$ and $\rho = 0.9$).

Fig. 8 shows SOR for the fractional threshold scheme over the traffic load ρ and the fractional threshold $t+\alpha$ when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$. As illustrated in this figure, SOR increases as the fractional threshold decreases. For a fixed threshold at a small value, when the traffic load increases, SOR increases since the system need to wake up more often; when the traffic load is high enough, SOR decreases since the system spends more time in the wake-up mode and less time in the sleep mode so that the SOR decreases.

Fig. 9 shows EC for the fractional threshold scheme over the traffic load ρ and the fractional threshold $t+\alpha$ when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$. As illustrated in the figure, EC increases as the fractional threshold decreases. For a fixed threshold at a small value, when the traffic load increases, EC increases since the system spends more time in the wake-up mode; when the traffic load is high enough, EC decreases since the system spends more time in the wake-up mode and less time in the sleep mode so that the SOR decreases. This observation is also because we use a large value for the EC for the switch-on action.

B. Comparisons of the Optimal Fractional Threshold Scheme With Other Schemes

Fig. 10 shows thresholds for *WA*, the optimal fractional threshold, and *WF* over the traffic load ρ, when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$ and the PDP bound is 3%. As illustrated in this figure, the optimal fractional threshold is in the interval between that of WA and that of WF. When the traffic load increases, the optimal fractional threshold deceases since the system needs to wake up earlier to handle more traffic. One important observation is that optimal thresholds are real numbers with nonzero fraction, instead of integers. Therefore, it is perfect to use the fractional threshold scheme to obtain optimal values.

Fig. 11 shows PDP for AOFF, WF, the optimal fractional threshold scheme, WA, and AON schemes over the traffic load ρ, when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$ and the PDP bound is 3%. As illustrated in this figure, AOFF has the highest PDP ($= 1$). WA and AON have the same PDP, i.e., the lowest PDP. PDP of the optimal fractional threshold scheme is between that of WA and WF. We observe that the optimal fractional threshold scheme is exactly bounded by 3%. Other schemes whose PDPs are bounded by 3% are AON and WA. However, later figures show that AON and WA have either very high EC or very high SOR.

Fig. 12 shows EC for AON, WA, the optimal fractional threshold scheme, WF, and AOFF schemes over the traffic load ρ, when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$ and the PDP bound is 3%. As illustrated in this figure, AON has the highest EC and AOFF has the lowest EC. EC of WF is higher than that of AOFF. EC of the optimal fractional threshold scheme is in between that of WA and that of WF. We observe that the optimal fractional threshold scheme has very low EC, and the only working scheme (AOFF is not a working scheme) that is lower than the optimal fractional threshold scheme is WF, which is only a little lower than the optimal fractional threshold scheme. From Fig. 11, AOFFs PDP is 1 and WF has much higher PDP than the optimal fractional threshold scheme.

Therefore, the optimal fractional threshold scheme is the best scheme in terms of optimizing the total EC with a bound on PDP.

Fig. 13 shows SOR for AON, WA, the optimal fractional threshold scheme WF and AOFF schemes over the traffic load ρ, when $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}} = 1 : 10 : 30 : 20$, and the PDP bound is 3%. As illustrated in this figure, WA has the highest SOR. AON and AOFF have the lowest SOR ($= 0$).

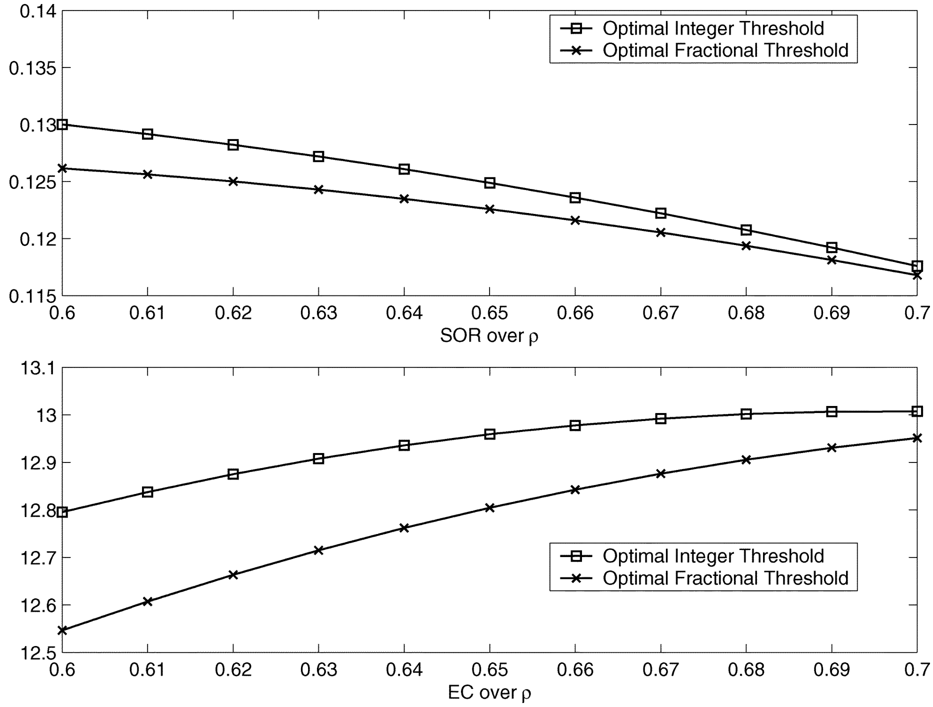

Fig. 16. Comparison of the optimal fractional threshold scheme and the optimal integer threshold scheme (*PDP* bound is 3%).

SOR of the optimal fractional threshold scheme is in between that of WA and that of WF. We observe that the optimal fractional threshold scheme has very low SOR, and the only working schemes (AOFF is not a working scheme) lower than the optimal fractional threshold scheme are WF and AON. From Fig. 11, AOFFs PDP is 1 and WF has much higher PDP than the optimal fractional threshold scheme.

Therefore, the optimal fractional threshold scheme is the best scheme in terms of optimizing the total SOR with a bound on PDP.

Fig. 14 shows EC for the optimal fractional threshold scheme over the traffic load ρ for different ratios of $E_S : E_W : E_{S-\mathrm{ON}} : E_{S-\mathrm{OFF}}$. As illustrated in the figure, as either $E_{S-\mathrm{ON}}$ or E_W increases relative to E_S, the total EC increases.

Fig. 15 shows SOR and EC versus PDP bound for the optimal fractional threshold scheme. As illustrated in the figure, as the PDP bound increases, both EC and SOR decrease. In other words, if we loosen the requirement of PDP, the system saves more energy.

Finally, Fig. 16 compares the optimal fractional threshold scheme with the optimal integer threshold scheme. The optimal integer threshold scheme is to find an optimal integer value with a bound on PDP. As illustrated in the figure, the optimal fractional threshold scheme is better than the optimal integer threshold scheme.

C. Summary and Key Results

Our goal is to minimize both the total EC and the SOR with a bound on the PDP. We summarize the key results as follows.

- As the fractional threshold increases, PDP increases, and both SOR and EC decrease.
- PDP increases when either the traffic load increases or the threshold increases.
- EC increases as the fractional threshold decreases. For a fixed threshold at a small value, when the traffic load increases, EC increases first and then decreases.
- SOR increases as the fractional threshold decreases. For a fixed threshold at a small value, when the traffic load increases, SOR increases first and then decreases.
- When the traffic load increases, the optimal fractional threshold decreases. One important observation is that optimal thresholds are real numbers with nonzero fraction, instead of integers. Therefore, it is perfect to use the fractional threshold scheme to obtain optimal values.
- AOFF has the highest PDP ($= 1$). WA and AON have the lowest PDP. PDP of the optimal fractional threshold scheme is between that of WA and WF. Given a bound on PDP, the optimal fractional threshold scheme is exactly bounded by the PDP. Other schemes that can meet a given PDP bound are AON and WA. However, AON and WA have either very high EC or very high SOR.
- AON has the highest EC and AOFF has the lowest EC. EC of WF is higher than that of AOFF. EC of the optimal fractional threshold scheme is in between that of WA and that of WF. The optimal fractional threshold scheme has very low EC, and the only working scheme that is lower than the optimal fractional threshold scheme is WF, which is only a little lower than the optimal fractional threshold scheme. However, WF has much higher PDP than the optimal fractional threshold scheme. Therefore, the optimal fractional threshold scheme is the best scheme in terms of optimizing the total EC with a bound on PDP.
- AON has the highest SOR. AON and AOFF have the lowest SOR ($= 0$). SOR of the optimal fractional

threshold scheme is in between that of WA and that of WF. The optimal fractional threshold scheme has very low SOR, and the only working schemes that are lower than the optimal fractional threshold scheme are WF and AON. AON and WF have much higher PDP than the optimal fractional threshold scheme. Therefore, the optimal fractional threshold scheme is the best scheme in terms of optimizing the total SOR with a bound on PDP.

- As either $E_{S-\mathrm{ON}}$ or E_W increases relative to E_S, the total EC increases.
- As the PDP bound increases, both EC and SOR decrease. In other words, if we loosen the requirement of PDP, the system saves more energy.
- The optimal fractional threshold scheme is better than the optimal integer threshold scheme.

Furthermore, simulation results and analytical results match pretty well.

VI. Conclusion

In this paper, we study the timing when mobile handset should wake up. We propose the fractional threshold scheme and prove that there is a unique optimal threshold to minimize both the total EC and the SOR with a bound on the PDP. We compare the optimal fractional threshold scheme with five other schemes including the optimal integer threshold scheme, and show that the optimal fractional threshold scheme is the best.

Appendix

Proof of (16) and (17)

Let ρ denote λ/μ. From (5)∼(7), we have

$$P_{1^*} = \frac{\lambda}{\mu P_0} = \rho P_0 \tag{39}$$

$$P_k = P_{k+1} \text{ for } 0 \le k \le t-2 \tag{40}$$

From (8), we have

$$P_t = \alpha P_{(t-1)} = \alpha P_0. \tag{41}$$

From (9) and (10), we have

$$P_{(i-1)^*} = (1+\rho^{-1})P_{i^*} - \rho^{-1}P_{(i+1)^*} \text{ for } (t+2) \le i \le N \tag{42}$$

$$P_{(N-1)^*} = \rho^{-1}P_{N^*}. \tag{43}$$

From (42) and (43), we can prove the following equation via mathematical induction:

$$P_{k^*} = \rho^{(k-N)}P_{N^*} \text{ for } (t+1) \le k \le N. \tag{44}$$

From (11) and (16), we have

$$P_{2^*} = \rho(1+\rho)P_0. \tag{45}$$

From (12), we have

$$P_{(i+1)^*} = (1+\rho)P_{i^*} - \rho P_{(i-1)^*} \text{ for } 2 \le i \le (t-1): \tag{46}$$

From (39), (45), and (46), we can prove the following equation via mathematical induction:

$$P_{k^*} = \frac{\rho(1-\rho^k)}{1-\rho}P_0 \text{ for } 1 \le k \le t. \tag{47}$$

By putting (40), (44), and (47), into (13), we have

$$\begin{aligned}
&\lambda\frac{\rho(1-\rho^{t-1})}{1-\rho}P_0 + (1-\alpha)\lambda P_0 + \mu\rho^{(t+1-N)}P_{N^*} \\
&\quad = (\mu+\lambda)\frac{\rho(1-\rho^t)}{1-\rho}P_0 \\
&(\mu+\lambda)\frac{\rho(1-\rho^t)}{1-\rho}P_0 - \lambda\frac{\rho(1-\rho^{t-1})}{1-\rho}P_0 - (1-\alpha)\lambda P_0 \\
&\quad = \mu\rho^{(t+1-N)}P_{N^*} \\
&\left[(1+\rho)\frac{\rho(1-\rho^t)}{1-\rho} - \rho\frac{\rho(1-\rho^{t-1})}{1-\rho} - (1-\alpha)\rho\right]P_0 \\
&\quad = \rho^{(t+1-N)}P_{N^*} \\
&\left[\frac{1-\rho^t+\rho-\rho^{t+1}-\rho(1-\rho^{t-1})}{1-\rho} - (1-\alpha)\right]P_0 \\
&\quad = \rho^{(t-N)}P_{N^*} \\
&\left[\alpha + \frac{\rho\,(1-\rho^t)}{1-\rho}\right]P_0 \\
&\quad = \rho^{(t-N)}P_{N^*}.
\end{aligned} \tag{48}$$

By putting (41), (44), and (47) into (14), we have

$$\begin{aligned}
&\lambda\alpha P_0 + \lambda\frac{\rho(1-\rho^t)}{1-\rho}P + \mu\rho^{(t+2-N)}P_{N^*} \\
&\qquad = (\mu+\lambda)\rho^{(t+1-N)}P_{N^*} \\
&\left[\lambda\alpha + \lambda\frac{\rho(1-\rho^t)}{1-\rho}\right]P_0 = \left[(\mu+\lambda)\rho^{(t+1-N)} - \mu\rho^{(t+2-N)}\right]P_{N^*} \\
&\left[\rho\alpha + \rho\frac{\rho(1-\rho^t)}{1-\rho}\right]P_0 = \left[(1+\rho)\rho^{(t+1-N)} - \rho^{(t+2-N)}\right]P_{N^*} \\
&\left[\alpha + \frac{\rho(1-\rho^t)}{1-\rho}\right]P_0 = \rho^{(t-N)}P_{N^*}.
\end{aligned} \tag{49}$$

We observe that (48) and (49) are the same. Putting (40), (41), (44), and (47) into (15), we have

$$\begin{aligned}
&tP_0 + \alpha P_0 + \sum_{k=1}^{t}\frac{\rho(1-\rho^k)}{1-\rho}P_0 \\
&\qquad + \sum_{k=t+1}^{N}\rho^{(k-N)}P_{N^*} = 1 \\
&tP_0 + \alpha P_0 + \frac{\rho}{1-\rho}P_0\left(t - \sum_{k=1}^{t}\rho^k\right) \\
&\qquad + \rho^{t+1-N}\sum_{k=0}^{N-t-1}\rho^k P_{N^*} = 1 \\
&tP_0 + \alpha P_0 + \frac{\rho}{1-\rho}P_0\left(t - \frac{\rho\,(1-\rho^t)}{1-\rho}\right) \\
&\qquad + \rho^{t+1-N}P_{N^*}\frac{(1-\rho^{N-t})}{1-\rho} = 1
\end{aligned}$$

$$tP_0 + \alpha P_0 + \frac{\rho}{1-\rho}P_0\left(t - \frac{\rho(1-\rho^t)}{1-\rho}\right) + \rho^{t+1-N}P_{N^*}\frac{(1-\rho^{N-t})}{1-\rho} = 1$$
$$tP_0 + \alpha P_0 + \frac{t\rho}{1-\rho}P_0 - \frac{\rho^2(1-\rho^t)}{(1-\rho)^2}P_0 + \frac{(1-\rho^{t-N})}{1-\rho^{-1}}P_{N^*} = 1$$
$$\left[t+\alpha+\frac{t\rho}{1-\rho}-\frac{\rho^2(1-\rho^t)}{(1-\rho)^2}\right]P_0 = 1 - \frac{(1-\rho^{t-N})}{1-\rho^{-1}}P_{N^*}$$
$$\left[t(1-\rho)+\alpha(1-\rho)+t\rho-\frac{\rho^2(1-\rho^t)}{(1-\rho)}\right]P_0 = 1-\rho-\frac{(1-\rho^{t-N})}{(1-\rho^{-1})(1-\rho)}P_{N^*}$$
$$\left[t+\alpha(1-\rho)-\frac{\rho^2(1-\rho^t)}{(1-\rho)}\right]P_0 = 1-\rho-\frac{(1-\rho^{t-N})}{(1-\rho^{-1})(1-\rho)}P_{N^*}$$
$$[t+\alpha(1-\rho)-\frac{\rho^2(1-\rho^t)}{1-\rho}]P_0 = 1-\rho+\rho(1-\rho^{t-N})P_{N^*}. \quad (50)$$

From (49) and (50), for $0 < \mathrm{t} < \mathrm{N}$, $0 < \alpha < 1$

Let $A = \alpha + (\rho(1-\rho^t)/(1-\rho))$, $B = t + \alpha(1-\rho) - (\rho^2(1-\rho^t)/(1-\rho))$, and $C = \rho(1-\rho^{t-N})$.

$$AP_0 = \rho^{(t-N)}P_{N^*} \quad (51)$$
$$BP_0 = 1-\rho+CP_{N^*}. \quad (52)$$

From (51) and (52), we have

$$B\frac{\rho^{(t-N)}P_{N^*}}{A} = 1-\rho+CP_{N^*} \Leftrightarrow B\frac{\rho^{(t-N)}P_{N^*}}{A} - CP_{N^*} = 1-\rho.$$

Then we can have (16) and (17).

Proof of Theorem I

Let $\mathrm{PDP}(t,\alpha) = A(1-\rho)/(B\rho^{t-N} - CA) \triangleq f_{(\alpha)}/g_{(\alpha)}$, where $f_{(\alpha)} = [\alpha + \rho(1-\rho^t)/(1-\rho)](1-\rho)$, and

$$g_{(\alpha)} = \left[t+\alpha(1-\rho)-\frac{\rho^2(1-\rho^t)}{1-\rho}\right]\rho^{t-N} - \rho(1-\rho^{t-N})\left[\alpha+\frac{\rho(1-\rho^t)}{1-\rho}\right].$$

We have

$$\frac{\partial f_{(\alpha)}}{\partial \alpha} = 1-\rho$$
$$\frac{\partial\left(g_{(\alpha)}\right)}{\partial \alpha} = (1-\rho)\rho^{t-N} - \rho(1-\rho^{t-N}) = \rho(\rho^{t-N-1}-1)$$
$$\frac{\partial(\mathrm{PDP}(t,\alpha))}{\partial\alpha} = \frac{g_{(\alpha)}\frac{\partial f_{(\alpha)}}{\partial\alpha} - f_{(\alpha)}\frac{\partial g_{(\alpha)}}{\partial\alpha}}{g^2{}_{(\alpha)}}$$
$$= g^{-2}{}_{(\alpha)}\{[t(1-\rho)+\alpha(1-\rho)^2-\rho^2(1-\rho^t)]\rho^{t-N} - \rho(1-\rho^{t-N})[\alpha(1-\rho)+\rho(1-\rho^t)] - \rho(\rho^{t-N-1}-1)[\alpha(1-\rho)+\rho(1-\rho^t)]\}$$
$$= g^{-2}{}_{(\alpha)}\{[t(1-\rho)+\alpha(1-\rho)^2-\rho^2(1-\rho^t)]\rho^{t-N} - \rho^{t-N}(1-\rho)[\alpha(1-\rho)+\rho(1-\rho^t)]\}$$
$$= g^{-2}{}_{(\alpha)}\rho^{t-N}[t(1-\rho)+\alpha(1-\rho)^2-\rho^2(1-\rho^t) - \alpha(1-\rho)^2 - \rho(1-\rho)(1-\rho^t)]$$
$$= g^{-2}{}_{(\alpha)}\rho^{t-N}[t(1-\rho)-\rho(1-\rho^t)].$$

Since $\alpha \in [0,1]$, $\rho \in (0,1)$ and $1 \le t < N$, we have $\partial(\mathrm{PDP}(t,\alpha))/\partial\alpha > 0$. Since t and α are the integral part and the fractional part, respectively, PDP is continuous with respective to $(t+\alpha)$. Therefore, the PDP $\mathrm{PDP(t,\alpha)}$ is a strictly increasing function of $\mathrm{t}+\alpha$. We can easily have $\partial(\mathrm{PDP}(t,\alpha))/\partial(t+\alpha) > 0$. For the SOR, we have

$$F_{\text{switch-on}}(t,\alpha) = \frac{\lambda(1-\rho)}{B-CA\rho^{N-t}} = \frac{\lambda(1-\rho)}{t+\alpha(1-\rho)-\frac{\rho^2(1-\rho^t)}{1-\rho}-\rho(1-\rho^{t-N})\left[\alpha+\frac{\rho(1-\rho^t)}{1-\rho}\right]\rho^{N-t}}$$
$$h_{(\alpha)} \doteq t+\alpha(1-\rho)-\frac{\rho^2(1-\rho^t)}{1-\rho} - \rho(1-\rho^{t-N})\left[\alpha+\frac{\rho(1-\rho^t)}{1-\rho}\right]\rho^{N-t}$$
$$\frac{\partial(F_{\text{switch-on}}(t,\alpha))}{\partial\alpha} = -\lambda(1-\rho)h^{-2}{}_{(\alpha)}\frac{\partial h_{(\alpha)}}{\partial\alpha} = -\lambda(1-\rho)h^{-2}{}_{(\alpha)}[1-\rho-\rho^{N-t+!}(1-\rho^{t-N})] = -\lambda(1-\rho)h^{-2}{}_{(\alpha)}(1-\rho^{N-t+!}).$$

Since $-\lambda(1-\rho)h^{-2}{}_{(\alpha)} < 0$ and $(1-\rho^{N-t+!}) > 0$, we have $\partial(F_{\text{switch-on}}(t,\alpha))/\partial\alpha < 0$

Based on the similar reason as that for the previous $\mathrm{PDP(t,\alpha)}$, the SOR $\mathrm{F_{switch\text{-}on}(t,\alpha)}$ is a strictly decreasing function. In other words, we have $\partial(F_{\text{switch-on}}(t,\alpha))/\partial(t+\alpha) < 0$.

Proof of Theorem II

$$g(\alpha) \equiv t+\alpha(1-\rho)-\frac{\rho^2(1-\rho^t)}{1-\rho} - \rho(1-\rho^{t-N})\left[\alpha+\frac{\rho(1-\rho^t)}{1-\rho}\right]\rho^{N-t}$$
$$P_S = (t+\alpha)P_0 = \frac{(t+\alpha)(1-\rho)}{g(\alpha)}$$
$$\frac{\partial P_S}{\partial\alpha}$$

$$\begin{aligned}\frac{\partial E_{total}}{\partial \alpha} &= \frac{\partial \left[E_W - (E_W - E_S)\, P_S + (E_{S-\mathrm{ON}} + E_{S-\mathrm{OFF}})\, F_{\text{switch-on}}(t,\alpha)\right]}{\partial \alpha} \\ &= \frac{-(E_W - E_S)\, \partial P_S}{\partial \alpha} + \frac{(E_{S-\mathrm{ON}} + E_{S-\mathrm{OFF}})\, \partial F_{\text{switch-on}}(t,\alpha)}{\partial \alpha} < 0.\end{aligned}$$

$$\begin{aligned}
&= \frac{\partial \left[\frac{(t+\alpha)(1-\rho)}{g(\alpha)}\right]}{\partial \alpha} \\
&= \frac{(1-\rho)g(\alpha) - (t+\alpha)(1-\rho)\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right]}{g^2(\alpha)} \\
&= \frac{(1-\rho)\left[g(\alpha) - (t+\alpha)\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right]\right]}{g^2(\alpha)}
\end{aligned}$$

$$\begin{aligned}
&g(\alpha) - (t+\alpha)\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right] \\
&= t + \alpha(1-\rho) - \frac{\rho^2(1-\rho^t)}{1-\rho} \\
&- \rho(1-\rho^{t-N})\left[\alpha + \frac{\rho(1-\rho^t)}{1-\rho}\right]\rho^{N-t} \\
&- (t+\alpha)\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right] \\
&= t + \alpha(1-\rho) - \frac{\rho^2(1-\rho^t)}{1-\rho} \\
&- \rho(1-\rho^{t-N})\left[\alpha + \frac{\rho(1-\rho^t)}{1-\rho}\right]\rho^{N-t} \\
&- t\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right] \\
&- \alpha\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right] \\
&= t\left[1 - (1-\rho) + \rho(1-\rho^{t-N})\rho^{N-t}\right] \\
&+ \alpha\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right. \\
&\left. -(1-\rho) + \rho(1-\rho^{t-N})\rho^{N-t}\right] \\
&- \rho(1-\rho^{t-N})\frac{\rho(1-\rho^t)}{1-\rho}\rho^{N-t} - \frac{\rho^2(1-\rho^t)}{1-\rho} \\
&= t\rho^{N+1-t} - \rho^{N-t}\frac{\rho^2(1-\rho^t)}{1-\rho} \\
&= \rho^{N+1-t}\left[t - \frac{\rho(1-\rho^t)}{1-\rho}\right] = \rho^{N+1-t}\left[t - \frac{\rho}{1-\rho}(1-\rho^t)\right] \\
&= \begin{cases} 0, & \text{if } t = 0 \\ > \rho^{N+1-t}[t-1] \geq 0 & \text{if } t \geq 1 \end{cases}.
\end{aligned}$$

Therefore, we have

$$\begin{aligned}\frac{\partial P_S}{\partial \alpha} &= \frac{(1-\rho)\left[g(\alpha) - (t+\alpha)\left[(1-\rho) - \rho(1-\rho^{t-N})\rho^{N-t}\right]\right]}{g^2(\alpha)} \\ &\geq 0.\end{aligned}$$

From (23) and (36), we have (see the equation at the top of the page).

Using the similar reasoning for $\mathrm{PDP}(t,\alpha)$ in the proof of Theorem I and based on the above inequality, we can easily prove $\partial E_{\text{total}}/\partial(\alpha + t) < 0$. □

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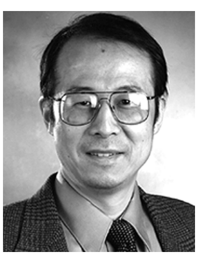

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