

LETTER

A Dynamic Sleep Interval Decision Scheme for Power-Saving with Minimum Delay in IEEE 802.16e Mobile WiMAX*

Bong Keol SHIN^(†a), Nonmember and Ju Wook JANG^(†b), Member

SUMMARY We observe that the state-of-the-art power-saving mechanisms (PSM) for IEEE 802.16e is neither optimal in terms of delay nor in terms of energy consumption. We propose a new PSM which achieves the optimality in terms of the average buffering delay without increasing energy consumption. In order to do so, we derive a formula which relates the average buffering delay to sleep intervals. Simulation results show that our scheme surpasses the BTE algorithm (used by the current IEEE 802.16e Mobile Stations) by 56.75–76% and the PSID algorithm by 8.52–24.39% in terms of the delay-energy consumption product.

key words: sleep interval decision, energy saving mechanism, WiMAX

1. Introduction

Various wireless network systems use power-saving mechanism (PSM) in which a mobile station (MS) changes its power level depending on its communication activity [1]–[5].

An MS in sleep mode wakes up at predefined wake-up intervals to check if there are any buffered packets waiting for it. If they exist, the MS stops entering sleep mode and receives them. An MS can save its battery power by being in sleep mode since it dissipates less energy than in wake-up mode or active mode [1]. Energy consumption and delay depend on the length of sleep intervals. If the length of sleep interval is long, more energy consumption is reduced with increased buffering delay. For short sleep intervals, energy consumption will be increased while buffering delay would be reduced. We propose a new PSM which achieves the optimality in terms of the average buffering delay without increasing energy consumption compare with the state-of-the-art Power-Saving Mechanisms (PSM) for IEEE 802.16e [2].

2. Related Work

The PSM in IEEE 802.16e [2] adopts a binary truncated exponent (BTE) algorithm to determine sleep intervals. After an MS negotiates its transition to sleep mode with the base

station (BS), it enters sleep mode, and thereafter, each sleep interval is doubled until a maximum is reached. If there are packets waiting for it, the MS terminates PSM (a series of sleep and wake-up mode) and enters always-active mode. The sleep intervals are determined by negotiation between each MS and the BS, and therefore they may differ among MSs. The length of i -th sleep interval is determined as

$$I_i = \begin{cases} I_{\min}, & \text{if } i = 1 \\ \min\{I_{\max}, 2^{i-1}I_{\min}\}, & \text{otherwise.} \end{cases} \quad (1)$$

The I_{\max} and I_{\min} denote the longest and shortest (initial) length of sleep interval defined in the BTE algorithm, respectively.

In [3], the authors proposed a probabilistic sleep interval decision (PSID) algorithm which improves the BTE algorithm. The PSID divides the delay into a fixed part (minimum delay) and a variable part based on the observation that the MS needs not wake up during the fixed part. The variable part is again divided into an extension-allowed interval and the rest. The lengths of sleep intervals are variable only within the extension-allowed interval which is set as $F_T(E[t] + k \cdot \sigma_T)$. $F_T(t)$ is a cumulative distribution function (CDF) of the response packet's arrival time and k is a real number. $E[t]$ and σ_T denote the mean and standard deviation of arrival time, t , respectively. So the probability $P_{tar}(k)$ that the response packet arrives within the extension-allowed interval can be represented as in Eq. (2).

$$P_{tar}(k) = F_T(E[t] + k \cdot \sigma_T). \quad (2)$$

The extension-allowed interval is divided into several sleep intervals for response packet to arrive at the BS during each sleep interval with the same probability. The sleep intervals outside the extension-allowed interval are fixed with the last interval from the extension-allowed interval.

Therefore, the length of the i -th sleep interval I_i is determined to satisfy Eq. (3).

$$\begin{cases} F_T\left(\sum_{k=1}^i I_k + a\right) = \frac{i \cdot P_{tar}(k)}{N_b} & \text{if } 1 \leq i \leq N_b \\ I_i = I_{N_b} & \text{otherwise} \end{cases} \quad (3)$$

where a is a fixed delay and N_b denotes the number of sleep intervals in the extension-allowed interval.

3. Delay Model

The round trip delay τ is the sum of the delay for MS to

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[†]The authors are with the Department of Electronic Engineering, Sogang University, Seoul 121-742, Korea.

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a) E-mail: sba@monet1.sogang.ac.kr

b) E-mail: jjang@sogang.ac.kr (Corresponding author)

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transmit the packets to BS ($\tau_{MS,BS}$), the delay for interchanging the packets between the BS and the server ($\tau_{BS,Server}$), and the delay for BS to transmit the packets to MS ($\tau_{BS,MS}$) [3]. It is represented as

$$\tau = \tau_{MS,BS} + \tau_{BS,Server} + \tau_{BS,MS}. \quad (4)$$

As $\tau_{MS,BS}$ and $\tau_{BS,MS}$ are the delays for transmitting the packets between MS and BS, they are much smaller than the delay that occurs between the BS and the server (i.e. $\tau_{BS,Server}$). Therefore, they are negligible and only $\tau_{BS,Server}$ is considered for round trip delay in this paper.

Generally, the delay of the wired environment can be divided into the fixed part and the variable part. Variable delay comes mainly from the queuing delay. To estimate the queuing delay, it is assumed that the queuing delay in the i -th router follows the exponential distribution with some rate (λ_i). Based on the assumption that the request-response packets are exchanged through the M routers between BS and server, the delay consumed from the i -th router to the $(i+1)$ -th router can be represented by Eq. (5) where a_i and X_i denote the fixed delay and the variable delay consumed from the i -th router to the $(i+1)$ -th router respectively [3].

$$Delay_i = X_i + a_i. \quad (5)$$

The queuing delay model follows the exponential distribution of the rate λ_i . Therefore, the total delay through the M routers between BS and the server is represented by Eq. (6).

$$\tau_{BS,Server} = \sum_{i=1}^M Delay_i = \sum_{i=1}^M X_i + a \quad (6)$$

where $a = \sum_{i=1}^M a_i$. The sum of the variable delay is $\sum_{i=1}^M X_i$, and it follows the hypo-exponential distribution because it is the sum of the exponential random variable that has an individual rate (λ_i). The probability density function (PDF) and the CDF of the hypo-exponential distribution are shown in Eq. (7).

$$\begin{aligned} f_T(t) &= \sum_{i=1}^M C_{i,M} \lambda_i e^{-\lambda_i(t-a)} \\ F_T(t) &= 1 - \sum_{i=1}^M C_{i,M} e^{-\lambda_i(t-a)} \end{aligned} \quad \text{for } t \geq a \quad (7)$$

where $C_{i,M} = \prod_{j \neq i} \lambda_j / (\lambda_j - \lambda_i)$.

4. The Proposed Scheme

We propose a new scheme to determine sleep intervals by using the PDF of the response packet's arrival time. The PSID algorithm [3] also uses the PDF of the response packet's arrival time in determining sleep intervals. In the PSID scheme, sleep intervals are set in such a way that the response packet may arrive at the base station during each sleep interval with the same probability. However, the PSID is not optimal in terms of the average buffering delay (A numerical example is provided in Sect. 5.1). Our observation is that in the PSID some intervals with thin PDF will contribute long delays to the average buffering delay.

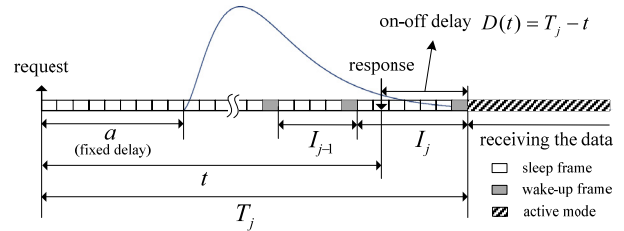


Fig. 1 The delay model used in our scheme.

Our scheme differs from the PSID algorithm in that it minimizes the average buffering delay by first deriving a formula which relates sleep intervals to the average buffering delay. Figure 1 shows the delay model used in our scheme where t and I_j represent the packet's arrival time and the size of the j -th sleep interval, respectively. Let $t \in I_j$ represents $T_{j-1} \leq t < T_j$ where j -th wake-up instant T_j is defined as in Eq. (8). The buffering delay can be represented by Eq. (9) if response packet arrives at time t . $p(t \in I_j)$ denotes the probability that response packet arrives during the j -th sleep interval and can be represented by Eq. (10).

$$T_j = \sum_{k=1}^j I_k + a. \quad (8)$$

$$D(t) = T_j - t \text{ for } t \in I_j. \quad (9)$$

$$\begin{aligned} p(t \in I_1) &= F_T(T_1) \\ p(t \in I_j) &= F_T(T_j) - F_T(T_{j-1}) \text{ for } j \geq 2 \end{aligned} \quad (10)$$

where $F_T(t)$ represents the CDF for the packet's arrival time t . From (8), (9) and (10), average buffering delay can be derived as

$$\begin{aligned} E[D(t)] &= \sum_{j=1}^{\infty} (E[D(t)|t \in I_j]) \cdot p(t \in I_j) \\ &= \sum_{j=1}^{\infty} E[T_j - t|t \in I_j] \cdot p(t \in I_j) \\ &\approx \sum_{j=1}^N T_j \cdot p(t \in I_j) - \sum_{j=1}^{\infty} E[t|t \in I_j] \cdot p(t \in I_j) \\ &= T_1 \cdot F_T(T_1) + \sum_{j=2}^N T_j \cdot \{F_T(T_j) - F_T(T_{j-1})\} - E[t] \end{aligned} \quad (11)$$

where N denotes the number of wake-up instants during the extension-allowed interval. (Note that $\sum_{j=1}^{\infty} E[t|t \in I_j] \cdot p(t \in I_j) = E[t]$) Our scheme aims to obtain a set of wake-up instants $T^* = \{T_1^*, T_2^*, \dots, T_N^*\}$ which minimizes $E[D(t)]$ in (11). For this, we take partial derivative of (11) with respect to T_1, T_2, \dots, T_N to obtain equations in (13). Note that two equalities in (12) are used in deriving Eq. (13). $\partial E[D(t)] / \partial T_j = 0$ for $j = 1, 2, 3, \dots, N-1$ can be represented by two equations (for $j = 1$ and for $j = 2, 3, \dots, N-1$, respectively) in Eq. (13).

$$\frac{\partial}{\partial T_j} E[t] = 0, \quad \frac{\partial}{\partial T_j} (T_m \cdot F_T(T_n)) = 0 \text{ if } m, n \neq j. \quad (12)$$

$$\begin{cases}
\frac{\partial}{\partial T_1} E[D(t)] = \frac{\partial}{\partial T_1} \left(T_1 F_T(T_1) + \sum_{j=2}^N T_j \{F_T(T_j)\} \right) \\
= F_T(T_1) + T_1 f_T(T_1) - T_2 f_T(T_1) = 0 \text{ and} \\
\frac{\partial}{\partial T_j} E[D(t)] = \frac{\partial}{\partial T_j} \left(T_1 F_T(T_1) + \sum_{j=2}^N T_j \{F_T(T_j)\} \right) \\
= \frac{\partial}{\partial T_j} \left(\sum_{j=2}^N T_j \cdot \{F_T(T_j) - F_T(T_{j-1})\} \right) \\
= \frac{\partial}{\partial T_j} \left(T_j \{F_T(T_j) - F_T(T_{j-1})\} - T_{j+1} F_T(T_j) \right) \\
= F_T(T_j) - F_T(T_{j-1}) + T_j f_T(T_j) - T_{j+1} f_T(T_j) = 0 \\
\text{for } j = 2, 3, \dots, N-1.
\end{cases} \quad (13)$$

We define a set $T^* = \{T_1^*, T_2^*, \dots, T_N^*\}$ to be the set $T = \{T_1, T_2, \dots, T_N\}$ which satisfies Eq. (13). Then, T^* denotes the set of wake-up instants which minimize $E[D(t)]$. We have Eq. (14) for set T^* from (13).

$$\begin{cases}
F_T(T_1^*) = (T_2^* - T_1^*) f_T(T_1^*) \\
F_T(T_j^*) - F_T(T_{j-1}^*) = (T_{j+1}^* - T_j^*) f_T(T_j^*) \\
\text{for } 2 \leq j \leq N-1.
\end{cases} \quad (14)$$

The set of the sleep intervals $I^* = \{I_1^*, I_2^*, \dots, I_N^*\}$ that minimizes the average buffering delay can be derived from the set T_i^* using Eq. (15).

$$\begin{cases}
I_1^* = T_1^* - a \\
I_j^* = T_j^* - T_{j-1}^* \quad \text{for } 2 \leq j \leq N.
\end{cases} \quad (15)$$

We summarize our scheme as below.

Step 1) Set the extension-allowed interval $[a, b]$ in a similar way to [3]. The “a” denotes the fixed delay between BS and the server while “b” is set to $E[t] + k \cdot \sigma_T$.

$E[t]$ denotes mean arrival time of response packet and σ_T denotes the standard deviation. The value k determines the target probability that t is included in the extension-allowed interval. (For example, if $k = 3$, then response packet may arrive within the extension-allowed interval with probability of 98.6%.)

Step 2) Choose the number of sleep intervals within the extension-allowed interval, N , considering the service type and traffic load.

Step 3) Obtain $T^* = \{T_1^*, T_2^*, \dots, T_N^*\}$ and $I^* = \{I_1^*, I_2^*, \dots, I_N^*\}$ using (14) and (15).

Step 4) Outside the extension-allowed interval, repeat I_N^* . This prevents the excessively long delays in response packet which arrived outside the extension-allowed interval.

5. Performance Evaluation

5.1 Numerical Analysis

The PSID is not optimal in terms of delay. We illustrate this using an example in Fig. 2 where $N = 2$, $k = 3$ and a hypo-exponential distribution with rate $\lambda_i = i/20$, $M = 3$ is assumed. Applying PSID by using (2) and (3), we have two wake-up instants, $T_{1,PSID} = 91.21$ (ms) and $T_{2,PSID} = 166.67$ (ms) as shown in the above of Fig. 2. The expected delay for PSID, $E[D(t)]_{PSID}$, is 31.26 (ms) from Eq. (16) with $N = 2$.

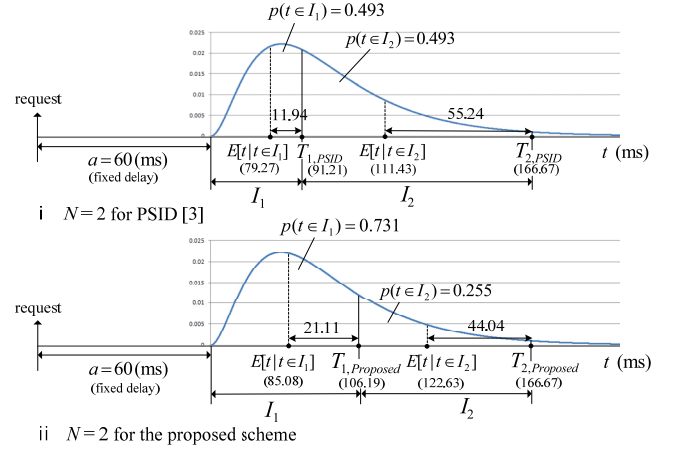


Fig. 2 PSID is not optimal in terms of delay (above: PSID, below: proposed).

Table 1 Simulation parameter.

Parameter	Definition	Value
M	The number of hops	3
a_i	The fixed delay from server i to server $i+1$	20(ms)
λ_i	The arrival rate in exponential distributed queuing delay for server i	$\frac{i}{20}$
fs	The frame size	5(ms)
P_{act}	Power consumption of an MS in active mode	1.5(W)
P_{slp}	Power consumption of an MS in sleep mode	0.045(W)

$$E[D(t)] = \sum_{j=1}^{\infty} (E[T_j - t | t \in I_j]) \cdot p(t \in I_j). \quad (16)$$

T_j depends on the scheme to be used, (PSID or the proposed algorithm). Our scheme chooses two wake-up times, $T_{1,Proposed} = 106.19$ (ms) and $T_{2,Proposed} = 166.67$ (ms) as in the below of Fig. 2. The expected delay for our scheme $E[D(t)]_{Proposed}$ is 24.27 (ms) from Eq. (16). Our scheme bests the PSID by 6.99 (ms) as shown in (17). This example shows that the PSID is not optimal in terms of expected buffering delay.

$$\begin{aligned}
E[D(t)]_{PSID} - E[D(t)]_{Proposed} \\
= 31.26 - 24.27 = 6.99 \text{ (ms)}. \quad (17)
\end{aligned}$$

The PSID [3] is not optimal in terms of energy consumption. The average energy consumptions can be obtained by Eq. (18) where fs denotes the frame size in IEEE 802.16e standard. P_{slp} or P_{act} represents power consumption during sleep mode or active mode, respectively.

$$E[C(t)] = \sum_{j=1}^{\infty} \{(T_j - j \cdot fs) P_{slp} + j \cdot fs \cdot P_{act}\} \cdot p(t \in I_j). \quad (18)$$

The average energy consumption for PSID, $E[C(t)]_{PSID}$ and that for our scheme, $E[C(t)]_{Proposed}$ are 16.47 (mW) and

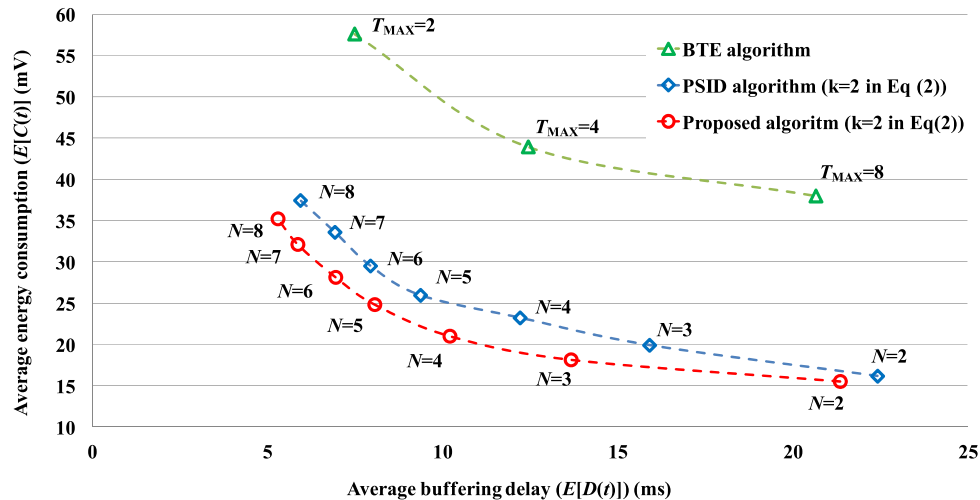


Fig. 3 Delay versus energy consumption for the BTE [2], PSID [3], and proposed scheme.

14.42 (mW), respectively from (19).

$$E[C(t)]_{PSID} - E[C(t)]_{Proposed} = 16.47 - 14.42 = 2.05 \text{ (mW)}. \quad (19)$$

This shows that the PSID algorithm is neither optimal in terms of expected delay nor in terms of energy consumption.

5.2 Simulation Result

Simulation is performed for the proposed scheme as well as known schemes (BTE [2], PSID [3]) using Monte Carlo method with the parameters in Table 1. The simulator written in C++ models the process that MS actually receives the data after it requests BS under the IEEE 802.16e Mobile WiMAX environment. Simulation is run 100,000 times. Figure 3 shows the delay and the energy consumption of our scheme compared with those of the BTE and PSID for various numbers of sleep intervals ($N = 2, 3, \dots, 8$) and $k = 2$ in Eq. (2). All the three schemes show trade-off between delay and the energy consumption. The trade-off curve of our algorithm is closest to the origin, exhibiting the best performance in terms of delay as well as energy consumption. We use a performance metric, $E[D(t) \times C(t)]$, which represents the delay multiplied by energy consumption. Our scheme bests the BTE by 56.75% ~ 76% and PSID by 8.52% ~

24.39% in this metric.

6. Conclusion

We proposed a new PSM which achieves the optimality in terms of the average buffering delay without increasing energy consumption compared with the state-of-the-art Power-Saving Mechanisms (PSM) for IEEE 802.16e [2]. For future work, we develop a sleep interval decision scheme for LTE systems.

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