Enhanced Power-Saving Mechanism to Maximize Operational Efficiency in IEEE 802.16e Systems

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***Abstract*—A Power-Saving Mechanism (PSM) operates with sleep-mode and wake-mode, based on the receipt of requests for transition to each mode. The sleep-mode operation is manipulated by adjusting operating parameters such as the minimum sleep interval (T_{min}) and the maximum sleep interval (T_{max}). Interestingly, both energy consumption and the response delay of the request for a BS initiation of awakening are reciprocally affected by the relative sizes of these two operating parameters compared to the sleep duration (from the beginning of sleep-mode to that of wake-mode). To resolve this issue, this paper proposes a new PSM, called EPSM, which adaptively and simultaneously controls the operating parameters by efficiently reflecting the sleep duration. Moreover, depending on the current remaining energy state, this mechanism can also increase the available sizes of the operating parameters to be manipulated for achieving more intensive energy conservation. A numerical model is developed with a Markov chain for performance evaluation of the proposed mechanism pertaining to energy consumption and the response delay. The evaluation results substantiate that this mechanism can enhance energy conservation within reasonable response delay compared to the standard mechanism. Moreover, under an insufficient remaining energy state, the EPSM can prolong battery life while enduring an increasing response delay.**

***Index Terms*—IEEE 802.16e, energy, power management, power-saving mechanism, sleep-mode.**

I. INTRODUCTION

THE Internet growth over recent decades has induced increasing demands for high speed and ubiquitous Internet access. To satisfy this requirement, much attention has been paid to Broadband Wireless Access (BWA), which aims to supply broad bandwidth at a low cost for small and residential business applications. Worldwide Interoperability for Microwave Access (WiMAX) [1], a standard technology, enables fixed and mobile convergence through BWA technology and flexible network architecture. As an extension of this technology, IEEE 802.16e (mobile WiMAX) [2] targets for service provisioning to Mobile Stations (MSs). In particular, its advanced Medium Access Control (MAC) architecture is able to support real-time applications such as Voice over IP (VoIP) in mobile environments with high data rate.

Since a Mobile Station (MS) is powered by a battery with limited capacity, the use of a Power-Saving Mechanism (PSM) becomes critical in IEEE 802.16e systems. Basically, a PSM operates with two modes: (i) *sleep-mode* and (ii) *wake-mode*. In sleep-mode, an MS repeatedly goes between a sleep state, where it does not communicate with a serving Base Station (BS); and a listening state, where it checks whether or not there is an awakening MAC Service Data Unit (SDU) for BS initiation of awakening the MS. The MS conserves energy by powering down during the sleep state and only powering up during the listening state [2]. Since energy consumed during the listening state is much greater than that during the sleep state [3], the reduction of the total duration of the listening state is the key to saving battery energy. The total durations of the listening state and sleep state are affected by two operating parameters: the minimum sleep interval (T_{min}) and the maximum sleep interval (T_{max}) [4]–[6]. Therefore, it is imperative to manipulate the optimal sizes of these two operating parameters.

Much of the research on this topic has mainly focused on improving power efficiency in the MAC layer. Particularly, there has been research progress for analyzing the performance of the standard PSM. This research has revealed that the operating parameters have to be manipulated in consideration of the *sleep duration* (from the beginning of sleep-mode to that of wake-mode) for enhancing PSM performance [5]–[7]. In addition to the analysis of the standard PSM, performance enhancement of PSM has been conducted; resulting in modification of the increase in sleep intervals [8], and a manipulation of the size of T_{min} [10], [11]. However, there has been no consideration of simultaneously manipulating the optimal sizes of both the operating parameters in tandem with the sleep duration. In addition, a method of reflecting the unpredictable sleep duration in deciding the operating parameters was not proposed, although both operating parameters are considered as a part of enhancement at the same time in [4].

Based on the previous studies, it is imperative to take into consideration (i) the need of the adaptive and simultaneous manipulation of optimal sizes of the operating parameters in tandem with the sleep duration [4]–[7], and (ii) the method of reflecting the unpredictable sleep duration in the manipulation [10], [11]. Moreover, the previous studies on PSM mostly focused on how to decrease energy consumption without consideration of the remaining energy state of an operating MS; and thus this paper takes the remaining energy state into account in PSM by dividing the overall operation into two parts: (i) *Condition A* for both energy conservation and the reduction of the response delay for receiving fast service requests under sufficient remaining energy, and (ii) *Condition B* for intensive energy conservation by sacrificing the response

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Manuscript received August 27, 2008; revised January 16, 2009 and March 21, 2009; accepted May 10, 2009. The associated editor coordinating the review of this paper and approving it for publication was F.-N. Pavlidou.

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Digital Object Identifier 10.1109/TWC.2009.081151

1536-1276/09$25.00

delay under insufficient remaining energy.

In order to satisfy these requirements, this paper proposes a new PSM, called EPSM, which adaptively and simultaneously controls the operating parameters by simply reflecting the size of the final sleep interval in the previous sleep-mode operation as a reference for considering the sleep duration trend. Besides, this mechanism can increase the available sizes of the operating parameters to be manipulated under an insufficient remaining energy state for achieving more intensive energy conservation. A numerical model is developed with Markov chain for performance evaluation of the proposed mechanism in light of energy consumption and the response delay. The evaluation results prove that this mechanism can achieve better energy conservation compared to the standard PSM and also considers the remaining energy state thus maximizing operational efficiency of the PSM.

To achieve this end, this paper is organized as follows. Section. 2 introduces the related work. The basic operation of the PSM in IEEE 802.16e and the effects of the operating parameters on PSM performance are presented based on the observation of the operating parameters in Section 3. Based upon the observations in Section 3, the operating procedure of the proposed mechanism is presented in Section 4. Then, analytical models for the standard and the proposed PSM are presented in Section 4. Section 5 shows performance evaluation results of our proposal. Finally, Section 6 concludes this paper.

II. RELATED WORKS

There have been many research efforts on PSM for improving MAC performance. Basically, the IEEE 802.16e standard document specifies the PSM in MAC protocol by defining three types of Power-Saving Class (PSC) [2]. In PSC I for Best Effort (BE) service and Non Real Time-Variable Rate (NRT-VR) service, the sleep interval increases exponentially from T_{min} and to T_{max} until there is no request to initiate wake-mode. In PSC II for Urgent Grant Service (UGS) and Real Time-Variable Rate (RT-VR) service, which are delay sensitive, the sleep interval is constantly set to T_{min} because the reduction of the response delay of awakening MAC SDUs is the most important. In PSC III for multicast connections as well as management operations, MSs, which are controlled simultaneously, automatically transit from sleep-mode to wake-mode without any request to initiate wake-mode because only the sleep state without the listening state exists during sleep-mode operation. Due to the importance of PSC application to all of the service types in IEEE 802.16e systems, performance of PSCs was studied in [12], and optimal selection of PSCs [13] was suggested according to the network traffic. Moreover, as applications of PSC I and II characteristics, PSC I is applicable to the short sleep duration for packet transmission duration of VoIP, and PSC II is adaptable to the long sleep duration for the mutual silence period of VoIP [14]. Also, a scheduling mechanism [15], including a periodic on-off scheme (PS) and an aperiodic on-off scheme (AS), was proposed using PSC II for satisfying the connection requiring the minimum delay requirement under a situation that there are several connections in an MS. But, BE and NRT-VR services were not considered, even though those are the dominant services on the Internet. However, due to the delay-sensitive characteristic of PSC II and group management characteristic of PSC III, PSC I is mainly treated as an enhancement of PSM performance. Thus, analysis and enhancement of PSM performance were conducted for PSC I as the main part of PSM.

As a part of PSM studies for analysis, performance of the standard PSM in terms of energy consumption and the response delay of awakening MAC SDUs over the average sleep duration, which are the most important performance metrics, were evaluated in [5]. Moreover, a performance comparison between MS and BS initiations of wake-mode according to their relative ratio was presented in [6]. Also, PSM was numerically analyzed with a Markov chain pertaining to the average energy consumption and the average response delay in consideration of the operating parameters in [7]. All these studies with their own methods of analysis present that there is an intimate relationship between the operating parameters and the sleep duration. Hence, it is imperative to importantly consider this aspect as a key part of performance enhancement of a PSM.

Recently, much research has been carried regarding the enhancement of PSM performance in reference to the aforementioned relationship. This enhancement was conducted with the modification of the increase of sleep intervals like that of the TCP congestion control mechanism [8], [9]. The contribution of these modifications is that the sleep duration can be reflected in the decision of the variance of sleep intervals. Specifically, the remaining energy state of an MS is reflected in the decision [9]. These, however, are not well-matched with the standard PSM in light of compatibility, because the sleep interval is doubled from the size of T_{min} to the size of T_{max} in the IEEE 802.16e standard document [2]. Moreover, adaptively manipulating the size of T_{min} was done by reflecting the state of the previous sleep-mode operation in order to consider the sleep duration [10], [11]. This can contribute energy conservation to the the system, but the two operating parameters were not taken into consideration at the same time for performance enhancement. Optimal sizes of both operating parameters depending on the average sleep duration were proposed in [4], whereas how to reflect the unpredictable sleep duration in deciding the sizes of operating parameters was not presented. Based upon the previous studies, it is imperative to taking into account (i) the requirement of the adaptive and simultaneous manipulation of optimal sizes of the operating parameters compared to the sleep duration [4]–[7], and (ii) the method of reflecting the unpredictable sleep duration in the manipulation [10], [11]. Moreover, the previous studies on PSM mostly focused on how to decrease energy consumption without consideration of the remaining energy state of an operating MS [4], [10], [11], [13], [14], even though prolonging the life of an MS is more preferable than the reduction of the response delay with intensive energy conservation under insufficient remaining energy.

III. AN OVERVIEW OF THE POWER-SAVING MECHANISM IN IEEE 802.16E

This section introduces the operation of the standard PSM in the IEEE 802.16e standard document [2] and presents key

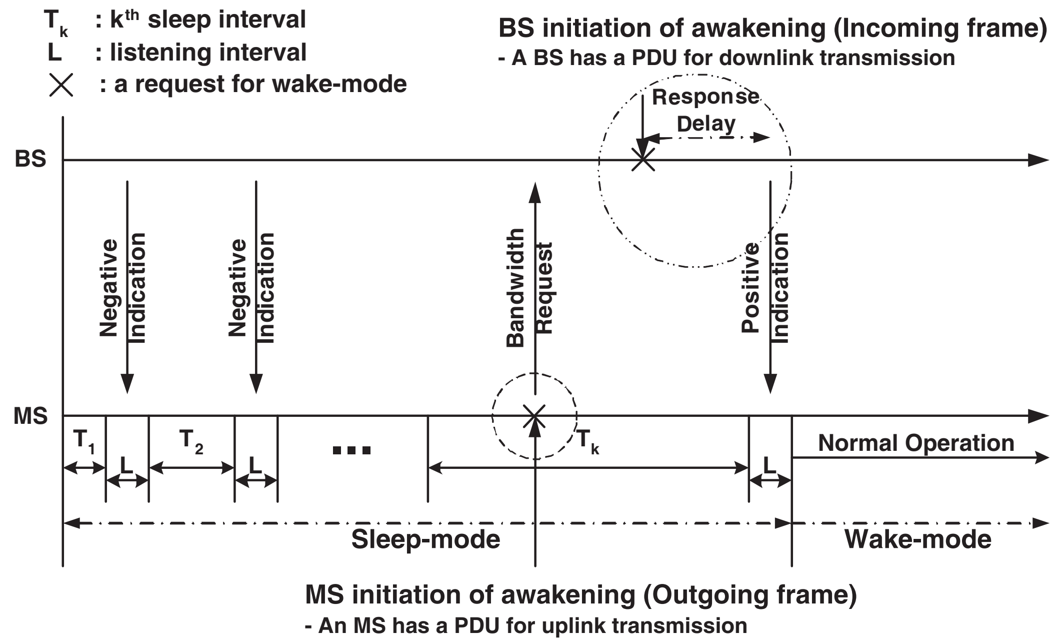


Fig. 1. Initiations of awakening.

ideas for enhancing its performance [4]. For saving energy, an MS repeatedly goes into wake-mode and sleep-mode by communicating with a serving BS. For mode switching from one to another, there is an *initiation of sleep-mode* for transition from wake-mode to sleep-mode and an *initiation of awakening* for transition from sleep-mode to wake-mode.

Initiation of sleep-mode is categorized by which station (MS or BS) initiates the sleep-mode of an MS, such as MS and BS initiations of sleep-mode. When an MS itself wants to be in sleep-mode (MS initiation of sleep-mode), it sends a BS a sleep request message (MOB-SLP-REQ), which includes information such as T_{min}, T_{max}, the listening interval (L), and so on. After the BS receives the MOB-SLP-REQ message, it sends the MS a sleep response message (MOB-SLP-RSP), which includes the beginning time of the sleep-mode (T_S), T_{min}, T_{max}, L, and so on. After the MS receives the MOB-SLP-RSP message, the MS begins sleep-mode. On the other hand, when a BS wants an MS to be in sleep-mode (BS initiation of sleep-mode), it sends the MS a MOB-SLP-RSP message. After the MS receives the MOB-SLP-RSP message, the MS starts sleep-mode. The MOB-SLP-RSP message is sent from the BS to an MS on its basic Connection Identifier (CID) in response to a MOB-SLP-REQ message or broadcast CID, or may be sent unsolicited.

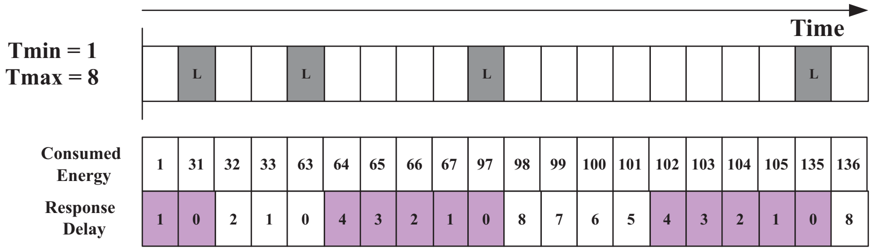
During sleep-mode operation, after the first sleep interval (T_1) (=T_{min}), an MS transits into a listening state waiting for a MOB-TRF-IND message to be transmitted from the BS. This message indicates whether or not there is any traffic addressed to the MS during the previous sleep interval. If the MOB-TRF-IND message indication is negative, the next sleep interval doubles from the preceding sleep interval and sleep-mode operation continues. This process is repeated until the sleep interval reaches T_{max}. Then, with IEEE 802.16e system parameters [2], the duration of the k^{th} sleep interval (T_k) is given by:

$$T_k \quad = \quad min(2 \cdot T_{pre}, B_f \cdot 2^{E_f}). \tag{1}$$

where T_{pre} is the previous sleep interval, B_f is the final sleep interval base, and E_f is the final sleep interval exponent (T_{max} = $B_f \cdot 2^{E_f}$). After the size of T_k reaches T_{max}, the sleep interval remains at T_{max} until the MS receives an awakening MAC SDU message to awaken.

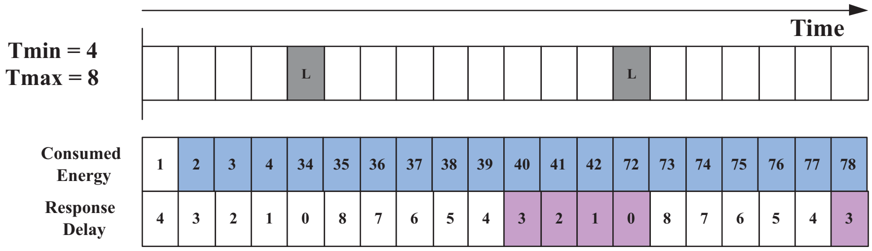
Fig. 1 exemplifies initiations of awakening by both the MS and BS. First, when an MS has some Protocol Data Units (PDUs) for the serving BS, the MS itself can go into wake-mode without any response delay. Then, the MS sends a bandwidth request message to the BS. Since there is no response delay in waiting for any messages to make an MS awaken, a longer sleep interval produces better power-saving gain. On the other hand, when the serving BS has some PDUs to be transmitted to the MS, it can initiate the MS awaken by sending an awakening MAC SDU to the MS during the listening state. In this case, the BS should wait to transmit awakening MAC SDUs until the listening state of the MS begins. Thus, BS initiation of awakening may cause an additional response delay.

For a more detailed explanation about PSM performance related to the operating parameters, it is assumed that the energy consumed during 1 unit of time (U) in the sleep state (E_S) is set to 1, and the energy consumed during $1U$ in the listening state is set to 30, respectively; so that the example will be easier to understand. Fig. 2 illustrates how T_{min} affects energy consumption and the response delay in light of PSM performance. Since an MS with $T_{min} = 1$ (Fig. 2.(a)) returns more often to the listening state than an MS with $T_{min} = 4$ (Fig. 2.(b)), the former affects less response delay. (In the figure, the numbers in each column indicate the response delay time that an MS affects when it wakes up at the time slot.) On the other hand, the latter produces



Tmin = 1 Tmax = 8		L			L					L									L	
Consumed Energy	1	31	32	33	63	64	65	66	67	97	98	99	100	101	102	103	104	105	135	136
Response Delay	1	0	2	1	0	4	3	2	1	0	8	7	6	5	4	3	2	1	0	8

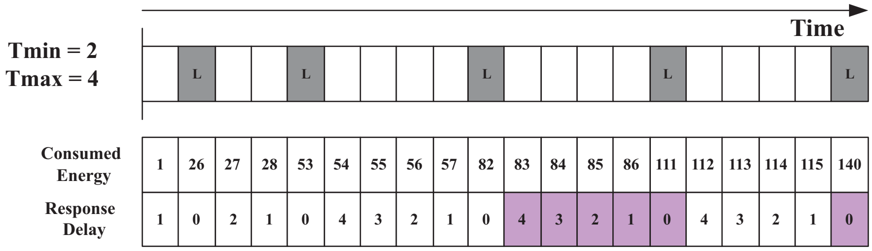
(a) Tmin = 1, Tmax = 8



Tmin = 4 Tmax = 8					L									L						
Consumed Energy	1	2	3	4	34	35	36	37	38	39	40	41	42	72	73	74	75	76	77	78
Response Delay	4	3	2	1	0	8	7	6	5	4	3	2	1	0	8	7	6	5	4	3

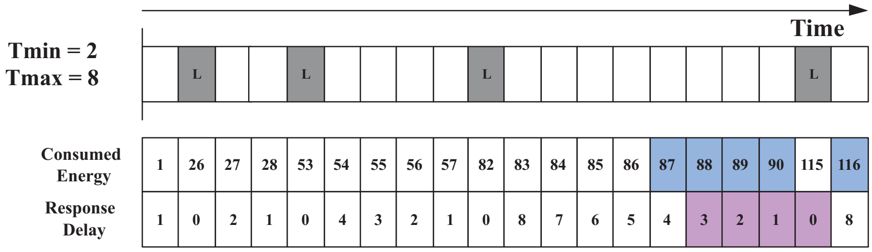
(b) Tmin = 4, Tmax = 8

Fig. 2. The effects of T_{min} on PSM performance (T_{max} = 8, E_S = 1, and E_L = 30) [4].



Tmin = 2 Tmax = 4		L			L					L					L					L
Consumed Energy	1	26	27	28	53	54	55	56	57	82	83	84	85	86	111	112	113	114	115	140
Response Delay	1	0	2	1	0	4	3	2	1	0	4	3	2	1	0	4	3	2	1	0

(a) Tmin = 2, Tmax = 4



Tmin = 2 Tmax = 8		L			L					L									L	
Consumed Energy	1	26	27	28	53	54	55	56	57	82	83	84	85	86	87	88	89	90	115	116
Response Delay	1	0	2	1	0	4	3	2	1	0	8	7	6	5	4	3	2	1	0	8

(b) Tmin = 2, Tmax = 8

Fig. 3. The effects of T_{max} on PSM performance (T_{min} = 2, E_S = 1, and E_L = 30) [4].

better energy conservation performance because it has fewer listening states. (The numbers in each column indicate the accumulated consumed energy from the beginning of sleep-mode to the current time slot.) As a result, a longer T_{min} generally induces better energy conservation but a worse response delay, and vice versa.

The effects of T_{max} on PSM performance are exemplified in Fig. 3. As expectedly, changes in T_{max} have reciprocal effects on energy consumption and the response delay, similar to the case of T_{min}. Differences between the effects of T_{min} and T_{max} come from the degree of sensitivity to the two performance metrics in a certain duration. When a BS initiation of awakening occurs under the k^{th} sleep interval $(T_k) < T_{max}$, a change of T_{min} is more sensitive than that of T_{max} in enhancing energy conservation. However, when the BS initiates awakening the MS under $T_k \geq T_{max}$, a change of T_{max} is more effective than that of T_{min} in reducing response delay. As a consequence of the observation of the operating parameters, it goes without saying that both operating parameters have to be taken into consideration for enhancing PSM performance [4], [5]. In the following section, our proposed mechanism will be presented in consideration of the aforementioned requirements.

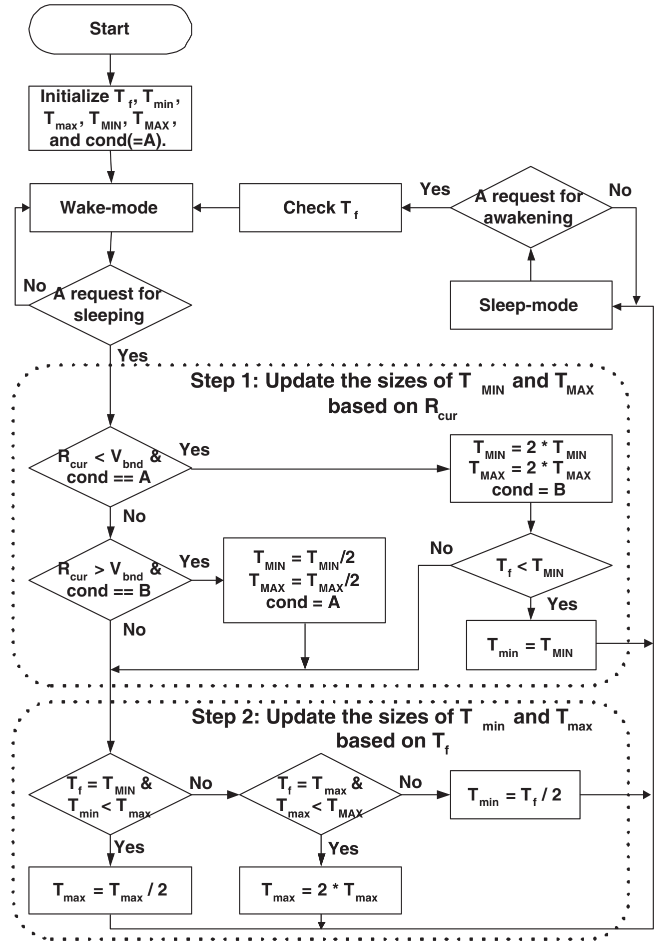


Fig. 4. Overall operating procedure of the EPSM.

IV. ENHANCED POWER-SAVING MECHANISM (EPSM)

Based on the observation of the effect of the parameters in consideration of the sleep duration (from the beginning of sleep-mode to that of wake-mode) on energy consumption and the response delay of awakening MAC SDUs to initiate awakening of an MS, this section proposes a new power-saving mechanism, which is designed to adaptively and simultaneously control the operating parameters by reflecting the sleep duration and the remaining energy state of an MS. Basically, this mechanism consists of two conditions which consider the remaining energy state: (i) Condition A for enhanced energy conservation with reasonable response delay by maintaining relevant sizes of sleep intervals (ii) Condition B for achieving more intensive energy conservation by keeping relatively larger sizes of sleep intervals. Depending on the condition, the available sizes of the operating parameters to be manipulated are set differently for achieving each target performance. The overall operating procedure of the proposed EPSM is illustrated in Fig. 4.

After turning on the power of an MS, the parameters involved in the EPSM (T_f: the final sleep interval in the previous sleep-mode, T_{min}, T_{max}, T_{MIN}: the smallest value that T_{min} can take, T_{MAX}: the largest value that T_{max} can take, and $cond$: current condition, where $cond = A$ or B) are initialized, and then the MS goes into wake-mode for normal operation. If a request for sleep-mode does not arrive, wake-mode will continue. Otherwise, the EPSM will conduct the following two steps to decide the operating parameters before entering sleep-mode: first, it will update the sizes of T_{MIN} and T_{MAX} depending on the remaining energy state; and second, it will update the sizes of T_{min} and T_{max} based on T_f. These two steps will be explained in detail in the following paragraphs.

A. *Step 1 for decision of condition with regards to the remaining energy state: Update the sizes of T_{MIN} and T_{MAX} based on R_{cur}.*

The first step is to check the level of the current remaining energy of an MS for which performance metrics will be considered more important. Based on this step, it is possible to control the available sizes of the operating parameters to be manipulated according to the remaining energy state. Let us define R_{cur}, as a ratio of the current remaining energy of an MS (E_R) to the total amount of energy of the MS (E_{tot}). This is given by:

$$R_{cur} = \frac{E_R}{E_{tot}}, \tag{2}$$

where $0 \leq R_{cur} \leq 1$.

Depending on the predefined boundary value (V_{bnd}), there are two conditions as follows:

(1) Condition A ($V_{bnd} \leq R_{cur} \leq 1$): This means that an MS has sufficient energy. Thus, we pay attention to not only energy conservation but also the reduction of the response delay time. Actually, this condition is considered the main operation of the EPSM because both metrics are considered important. Due to the high level of remaining energy, the EPSM does not take any action in Step 1, and the parameter involved in the EPSM, *cond*, is set to *A*.

(2) Condition B ($0 \leq R_{cur} < V_{bnd}$): This implies that an operating MS has insufficient energy to fully support normal operation. Thus, we put more attention on intensively reducing energy consumption without concerning about the reduction of the response delay. Thus, the EPSM increases the available sizes of the operating parameters to be manipulated, namely, T_{MIN} and T_{MAX} limiting the available sizes of T_{min} and T_{max} are doubled. At this point, the parameter, *cond*, is set to *B*. In exceptional cases where the initial size of T_f is not between T_{MIN} and T_{MAX}, for example when T_f is smaller than T_{MIN}, T_{min} is set to T_{MIN}, and then it directly goes into sleep-mode. Otherwise, the process proceeds to Step 2. On the other hand, if the energy of the operating MS is recharged and thus $V_{bnd} \leq R_{cur} \leq 1$ during Condition B, T_{MIN} and T_{MAX} will be set to halves of the current T_{MIN} and T_{MAX} and *cond* will be set to *A* because the current remaining energy is sufficient. Differing from Condition A, this condition is the sub-operation of the EPSM because under this condition the EPSM can cause more response delay compared to the standard PSM although it can intensively reduce energy consumption.

B. *Step 2 for decision of the sizes of the operating parameters by reflecting the sleep duration trend: Update the sizes of T_{min} and T_{max} based on T_f.*

This step updates the sizes of T_{min} and T_{max} based on T_f to reflect the sleep duration trend. During one sleep-mode operation, if there is no initiation of awakening in each sleep cycle, the size of the operating sleep interval doubles from the size of the previous sleep interval until it reaches T_{max}. When an initiation of awakening occurs, T_{min} and T_{max} are newly updated based on the following policy:

(1) If T_f is equal to T_{MIN} and T_{min} is smaller than T_{max}, then T_{max} is regarded as a relatively larger size compared to the sleep duration. Thus, T_{max} is set to half of the T_{max} in the previous operation.

(2) Or, if T_f is equal to T_{max} and T_{max} is smaller than T_{MAX}, T_{max} doubles, because T_{max} is considered to be a relatively smaller size compared to the sleep duration.

(3) Otherwise, T_{min} is updated to half of the T_f.

By applying the EPSM to IEEE 802.16e systems, the total duration of the listening state, which consumes much more energy than the sleep state, can be kept at the smallest length possible. So energy consumption can be much reduced, while the response delay time will be kept at a reasonable level compared to the standard PSM under various situations of the sleep duration.

V. ANALYTICAL MODELS

This section presents analytical models for the standard PSM and EPSM. Each request to initiate awakening of an MS is assumed to be initiated under a Poisson process with rate λ (requests per unit of time (U)). Thus, the request duration of each initiation of awakening is exponentially distributed, and set to the sleep duration, the duration from the beginning time of sleep-mode of an MS to the beginning time of wake-mode. Thus, the average sleep duration (T_I) is $\frac{1}{\lambda}$. It is assumed that the listening interval (L) is a fixed length. According to the standard PSM [2], the duration of the k^{th} sleep interval (T_k) is obtained by:

$$T_k = \begin{cases} 2^{k-1} T_{min}, & \text{for } 1 \leq \text{k} < \text{N}, \\ T_{max}, & \text{for k} \geq \text{N}, \end{cases} \tag{3}$$

N is the value of k when T_k = T_{max}.

The duration of the k^{th} sleep cycle (C_k) is given by:

$$C_k = T_k + L. \tag{4}$$

The probability that there is no initiation of awakening during C_k is then obtained by:

$$P_k = e^{-\lambda C_k}, \ 1 \leq k \leq N, \tag{5}$$

Thus, the probability that there is at least one initiation of awakening during C_k is 1-$e^{-\lambda C_k}$.

Consequently, the probability that there is at least one initiation of awakening in the k^{th} sleep cycle during one sleep-mode operation is given by:

$$P_k^S = \sum_{a=0}^{k-1} P_a \cdot (1 - P_k) = e^{-\lambda \sum_{a=0}^{k-1} C_a}(1 - e^{-\lambda C_k}). \tag{6}$$

A. *The Standard Power-Saving Mechanism*

The arrivals are random to the sleep intervals because requests to initiate awakening follow a Poisson process; hence, the average response delay of awakening MAC SDUs in BS initiation of awakening ($E[R]$) is given by [5]:

$$E[R] \ = \ \sum_{k=1}^{\infty} P_k^S \cdot \frac{C_k}{2}. \tag{7}$$

The average total period of the listening state, which consumes a much greater amount of energy than the sleep state, in an overall sleep-mode operation ($E[n]$) is given by [5]:

$$E[n] \ = \ \sum_{k=1}^{\infty} k \cdot P_k^S. \tag{8}$$

The average energy consumption in a BS initiation of awakening ($E_B[C]$) is calculated by [5]:

$$E_B[C] \ = \ \sum_{k=1}^{\infty} P_k^S \sum_{a=1}^{k} (T_a E_S + L E_L), \tag{9}$$

where E_S is the consumed energy per $1U$ during sleep intervals, and E_L is the same during listening intervals.

The average energy consumption in an MS initiation of awakening ($E_M[C]$) is achieved by subtracting the energy consumed during the response delay from $E_B[C]$. So, it is given by:

$$E_M[C] = \sum_{k=1}^{\infty} P_k^S (\sum_{a=1}^{k-1} (T_a E_S + L E_L) + \frac{T_a E_S}{2}). \tag{10}$$

B. *Enhanced Power-Saving Mechanism*

In addition to the analytical model for the standard PSM, the analytical model for the EPSM will now be exemplified. In order to compare the EPSM with the standard PSM, this model is extended from [5], which is used for the standard PSM, by applying the two dimensional Markov chain, as shown in Fig. 5. Let $\pi_{i,j}$ be the steady state probability when $T_{max} = 2^{M-1-i} \cdot T_{MIN}$ $(0 \leq i \leq M-1)$, and the size of operating sleep interval during overall sleep-mode operation, $T_j = 2^j \cdot T_{MIN}$ $(0 \leq j \leq M-i-1)$, where T_{MAX} = 2^{M-1} T_{MIN}. We have the following steady state equations:

For $j = 0$, we have

$$0 = \pi_{i,j}(-1) + \pi_{i,j+1}(1 - P_j), \tag{11}$$

where $i = 0$,

$$0 = \pi_{i-1,j}(1 - P_j) + \pi_{i,j}(-1) + \pi_{i,j+1}(1 - P_{j+1}), \tag{12}$$

where $1 \leq i \leq M-3$,

$$0 = \pi_{i-1,j}(1 - P_j) + \pi_{i,j}(-1) + \pi_{i+1,j}(1 - P_j), \tag{13}$$

where $i = M-2$, and

$$0 = \pi_{i,j}(-(1 - P_j)) + \pi_{i-1,j}(1 - P_j), \tag{14}$$

where $i = M-1$.

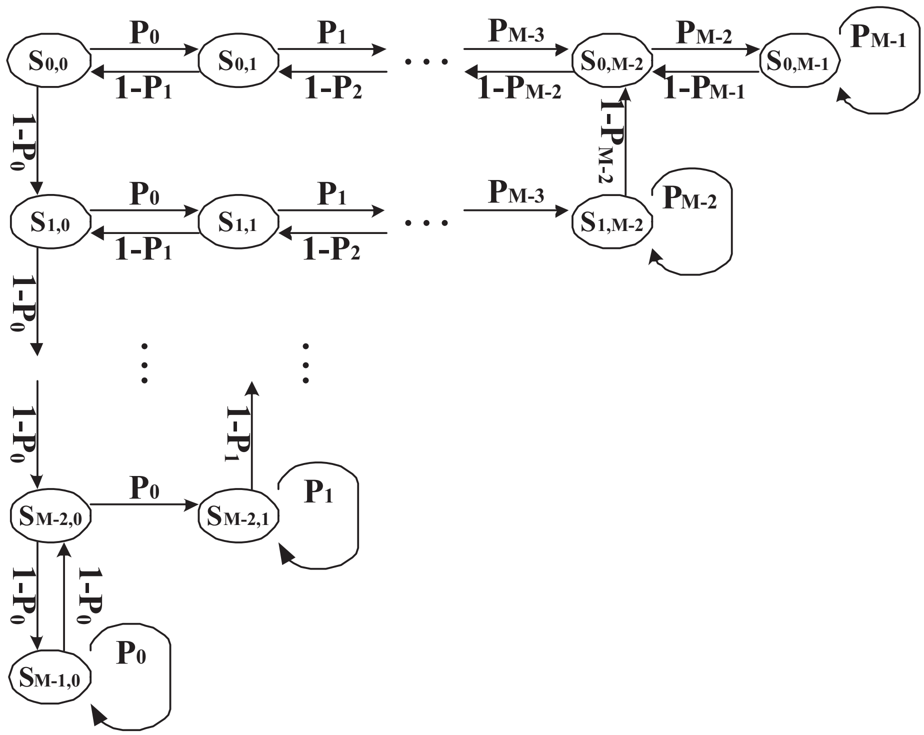


Fig. 5. Markov chain for the EPSM.

For $1 \leq j \leq M - i - 3$, we have

$$0 = \pi_{i,j-1}(P_{j-1}) + \pi_{i,j}(-1) + \pi_{i,j+1}(1 - P_{j+1}), \quad (15)$$

where $0 \leq i \leq M - 3$,
For $j = M - i - 2$, we have

$$\begin{aligned} 0 \; = \; & \pi_{i,j-1}(P_{j-1}) + \pi_{i,j}(-1) \\ & + \pi_{i,j+1}(1 - P_{j+1}) + \pi_{i+1,j}(1 - P_j), \end{aligned} \quad (16)$$

where $i = 0$, and

$$0 \; = \; \pi_{i,j-1}(P_{j-1}) + \pi_{i,j}(-1) + \pi_{i+1,j}(1 - P_j), \quad (17)$$

where $1 \leq i \leq M - 3$.
For $j = M - i - 1$, we have

$$0 = \pi_{i,j-1}(P_{j-1}) + \pi_{i,j}(-(1 - P_j)), \quad (18)$$

where $0 \leq i \leq M - 2$.

For brevity, $\pi_{i,j}$ values out of the range ($0 \leq i \leq M - 1$ and $0 \leq j \leq M - i - 1$) take the value zero.

Then, we also have the normalization equation:

$$\sum_{i=0}^{M-1} \sum_{j=0}^{M-1+i} \pi_{i,j} = 1. \quad (19)$$

The average response delay of awakening MAC SDUs in BS initiation of awakening is given by:

$$E[R] \; = \; \sum_{i=0}^{M-1} \sum_{j=0}^{M-1+i} \pi_{i,j} \sum_{k=j+1}^{\infty} P_k^S \cdot \frac{C_k}{2}. \quad (20)$$

The average total period of the listening state, which consumes a much greater amount of energy than the sleep state, in an overall sleep-mode operation ($E[n]$) is obtained by:

$$E[n] \; = \; \sum_{i=0}^{M-1} \sum_{j=0}^{M-1+i} \pi_{i,j} \sum_{k=j+1}^{\infty} k \cdot P_k^S. \quad (21)$$

The average energy consumption in BS initiation of awakening is given by:

$$E_B[C] = \sum_{i=0}^{M-1} \sum_{j=0}^{M-1+i} \pi_{i,j} \sum_{k=j+1}^{\infty} P_k^S \sum_{a=j+1}^{k} (T_a E_S + L E_L), \quad (22)$$

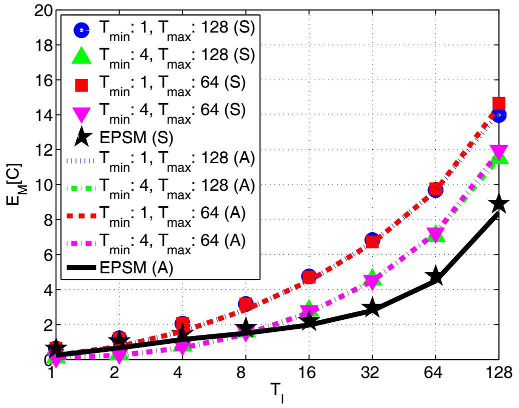
where E_S is the consumed energy per $1U$ during sleep intervals, and E_L is the same during listening intervals.

The average energy consumption in an MS initiation of awakening is achieved by subtracting the energy consumed during the average response delay from $E_B[C]$. So, it is obtained by:

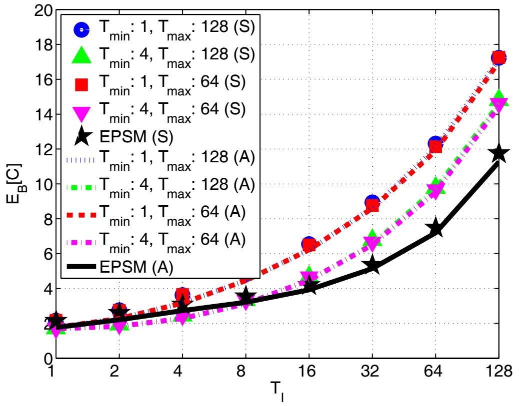
$$\begin{aligned} E_M[C] = & \sum_{i=0}^{M-1} \sum_{j=0}^{M-1+i} \pi_{i,j} \sum_{k=j+1}^{\infty} P_k^S \sum_{a=j+1}^{k-1} (T_a E_S + L E_L) \\ & + \sum_{i=0}^{M-1} \sum_{j=0}^{M-1+i} \pi_{i,j} \sum_{k=j+1}^{\infty} P_k^S \frac{T_k E_S}{2}. \end{aligned} \quad (23)$$

VI. PERFORMANCE EVALUATION

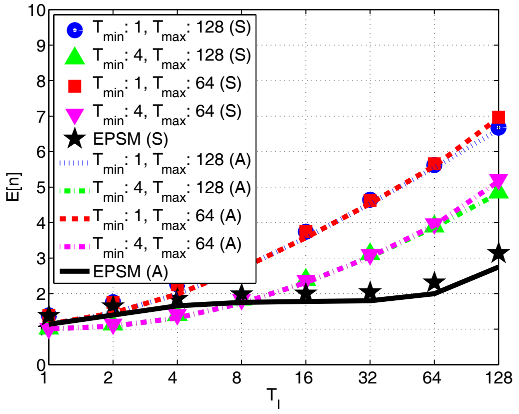
This section evaluates EPSM performance with the following assumptions [4]–[6], [10]: (i) energy consumed and the response delay during a sleep-mode operation of an MS are observed where there are ten MSs and one BS, (ii) the request period of an initiation of awakening is set to the sleep duration during one sleep-mode, and (iii) wake-mode is not considered as a part of the performance evaluation. On the other hand, parameters for evaluation are as follows: L = $1U$,



(a) The average energy consumed in an MS initiation of awakening



(b) The average energy consumed in a BS initiation of awakening



(c) The average total period of the listening state in an overall sleep-mode operation

Fig. 6. Performance comparison between the standard PSM and the EPSM during Condition A. (S: Simulation, A: Analysis)

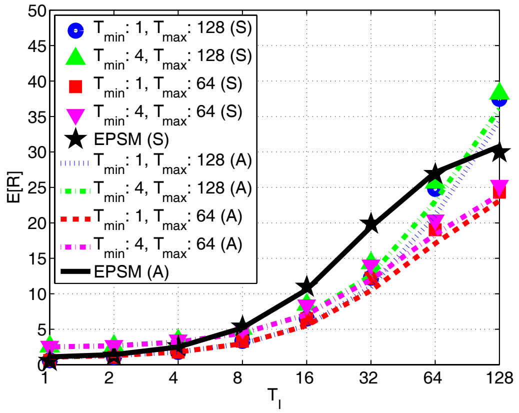


Fig. 7. The average response delay time of awakening MAC SDUs in a BS initiation of awakening during Condition A (S: Simulation, A: Analysis).

E_S = 0.045Watts (W), E_L = 1.4W [3], T_{MIN} = $1U$, and T_{MAX} = $64U$ (M=7). For the EPSM, the initial values of T_{min}, T_{max}, and T_f are set to $1U$, $64U$, and $1U$, respectively.

A. Performance of the EPSM under the Sufficient Energy State of an MS (Condition A)

We first observe the performance of the standard PSM and the main operation of the proposed EPSM under the sufficient energy state (Condition A). The average energy consumed in an MS initiation of awakening ($E_M[C]$) and that in a BS initiation of awakening ($E_B[C]$) are shown in Fig. 6 (a) and (b), respectively. In both cases, the overall range of T_I (the average sleep duration), energy consumed with $T_{min} = 1U$ is higher than that with $T_{min} = 4U$, regardless of T_{max}. This result concludes that T_{min} is a critical factor in energy consumption. Importantly, from Fig. 6(c) showing the average total period of the listening state ($E[n]$), which consumes much greater energy than the sleep state, the EPSM produces a smaller $E[n]$ than the standard PSM in most ranges of T_I except at the low range. Since the average total period of the listening state directly affects energy consumption, $E_M[C]$ and $E_B[C]$ under the EPSM are smaller than the standard PSM. As T_I increases, the degree of enhancement of $E_M[C]$ and $E_B[C]$ also increases, because the EPSM maintains the $E[n]$ as a small value as possible, while energy consumption in the standard PSM simply comes to increase the $E[n]$. Therefore, based on the observation of $E_M[C]$, $E_B[C]$, and $E[n]$, it is obvious that there is an intimate relationship between energy consumption and the average period of the listening state.

The average response delay time of awakening MAC SDUs in a BS initiation of awakening ($E[R]$) is shown in Fig. 7. When T_I ranges from 32 to $128U$, the average response delay time in the case of T_{max} = $128U$ is higher than that in the case of T_{max} = $64U$. This means that T_{max} can have more impact on response delay than T_{min}. On the other hand, the EPSM produces a slightly longer $E[R]$ than the standard PSM in the middle range of T_I. As presumed from Fig. 6(c), a smaller period of the listening state induces a longer response delay time in the EPSM.

B. Performance of the EPSM over Operation Time in Consideration of the Remaining Energy State

Now, let us observe the benefits of the EPSM based on simulation results over operation time. The parameters for evaluation are as follows: M = 7, and the total energy of an MS (E_{tot}) is 10000 $Joules$ (J). The condition of an operating MS changes from A to B when half of the total energy remains ($V_{bnd} = 0.5$) as an illustration of EPSM operation. Then, in Condition A (under a sufficient remaining energy state), T_{MIN} and T_{MAX} are set to $1U$ and $64U$, respectively. Furthermore,

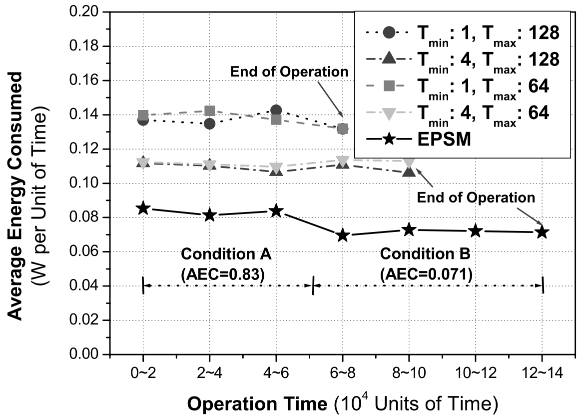


Fig. 8. The average energy consumed per $20000U$ over overall operation time in a BS initiation of awakening in consideration of Conditions A and B (T_I = $64U$).

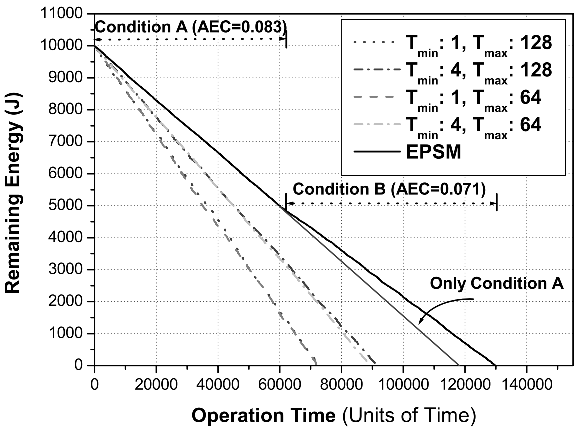


Fig. 10. The remaining energy of an operating MS in a BS initiation of awakening in consideration of Conditions A and B (T_I = $64U$).

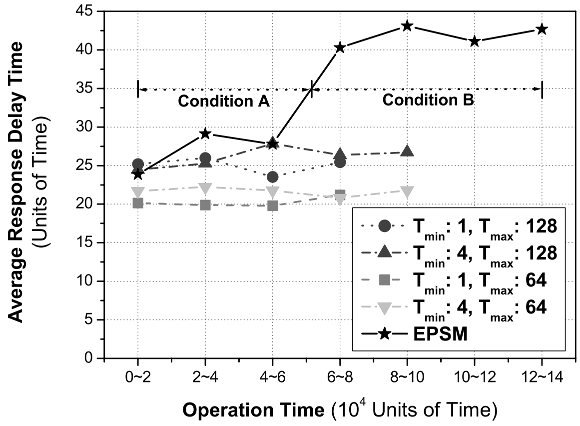


Fig. 9. The average response delay time per each $20000U$ in a BS initiation of awakening in consideration of Conditions A and B(T_I = $64U$).

in Condition B (under an insufficient remaining energy state) for intensive energy conservation, T_{MIN} and T_{MAX} are set to $2U$ and $128U$, respectively. To easily measure the performance of each condition of an MS, we define the average energy consumed per each condition (AEC) as the following equation:

$$AEC = \frac{energy\ consumed\ during\ a\ condition}{total\ operation\ time\ during\ a\ condition}, \quad (24)$$

where AEC means the decreasing slope of remaining energy during a specific condition (Condition A or B).

Figs. 8 and 9 show the average energy consumed and response delay time per $20000U$ over the overall operation time in a BS initiation of awakening in consideration of Conditions A and B. The operation time utilizing the EPSM can be extended due to the enhanced energy conservation in both Conditions A and B. Specifically, AEC at Condition A is 0.083 in the case of BS initiation of awakening, while keeping the average response delay time similar to that under the standard mechanism. As the remaining energy decreases and becomes insufficient, the condition changes from A to B. Then, AEC at Condition B decreases and comes to 0.071 in the case of a BS initiation of awakening, whereas the average response delay time is greater than that under Condition A and the standard PSM. As a consequence, enhanced energy conservation under Condition A and intensive energy conservation under Condition B can be achieved for prolonging the life of the MS as shown in Fig. 10.

In order to balance energy consumption and the response delay time, we can adjust the value of V_{bnd} (boundary value), which can control the condition switching time between Condition A and B according to the remaining energy state of an MS in consideration of application characteristics. In a case where Condition B is not significantly necessary to UGS or RT-VR service connection (i.e., delay-sensitive applications of an operating MS), V_{bnd} can be set to be much lower (e.g., 0.005 or less) in order to keep to reduce the response delay in MS operation. However, for a case where there will be no significant problem due to the increased response delay under Condition B with BE or NRT-VR service connection (e.g., FTP), V_{bnd} can be set higher (e.g., 0.01). Consequently, depending on the characteristics of applications, V_{bnd} can be decided adaptively.

VII. CONCLUSION

In this paper, we proposed an Enhanced Power Saving Mechanism for the IEEE 802.16e systems. Improving upon the standard mechanism, the EPSM adaptively decides the sizes of T_{min} and T_{max} by taking into account the sleep duration in the previous sleep-mode operation. Moreover, for real-life use, the EPSM can adaptively control energy consumption and the response delay of awakening MAC SDUs depending on the remaining energy of an operating MS. Our analytical and simulation results showed that the proposed mechanism achieved better performance in energy consumption by minimizing the average period of the listening state with operational efficiency. Then, enhanced energy conservation performance compensated for the deterioration of the response delay.

ACKNOWLEDGMENT

This work was supported in part by the MIC, Korea under the ITRC program (C-1090-0603-0036) supervised by IITA.

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