Scheduled Power-Saving Mechanism to Minimize Energy Consumption in IEEE 802.16e Systems

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***Abstract*—A Mobile Station in IEEE 802.16e operates power management using sleep-mode operation with one or more connections supporting several applications. After all of the connections of an MS transit into the sleep state, the MS powers down and then goes into an unavailable state without communicating with the serving Base Station. To improve energy conservation, this letter proposes a new Scheduled Power-Saving Mechanism, which schedules sleep-mode operations for connections, which newly initiate sleep-mode, by controlling operating parameters, such as the minimum sleep interval (T_{min}) and the maximum sleep interval (T_{max}), and the initiation time of sleep-mode operations of low Quality of Service (QoS) connections. Performance results show that the proposed mechanism can reduce the available state of an MS through this scheduling, and thus achieve better energy conservation of the MS than the standard mechanism.**

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

I. Introduction

IEEE 802.16E (mobile WiMAX) [1] specifies a standard power-saving mechanism (PSM), which controls sleep-mode and wake-mode for efficient power management of a Mobile Station (MS). In particular, during a sleep-mode operation, an MS repeatedly goes between a sleep state (no communications with the serving Base Station (BS)) and a listening state (waiting to receive Medium Access Control (MAC) messages to check whether or not the serving BS wants to awaken the MS). An MS conserves battery energy by powering down during the sleep state and only powering up during the listening state [1]. So, the key to saving battery energy is to reduce the total time of the listening state included in each sleep cycle [2]. The number of sleep cycles is decided by the sleep duration from the initiation time of sleep-mode of an MS to the awakening time, and two operating parameters: the minimum sleep interval (T_{min}) and the maximum sleep interval (T_{max}) [2]–[4]. Manipulating the values of the two parameters is an efficient way to reach target performance because they are controllable, whereas external sleep time is uncontrollable.

In IEEE 802.16e systems, Orthogonal Frequency Division Multiple Access (OFDMA) systems, an MS has one or more connections for several applications. Fig. 1 exemplifies the behavior of an MS operating in sleep-modes for two connections: Connection A (CA) for Urgent Grant Service (UGS) and Connection B (CB) for Best Effort (BE) service. In each connection, there are two states of the MS: (i) an *available state*, where the MS sends or receives MAC frames, and (ii) an *unavailable state*, where there is no communication between the MS and the serving BS, and thus the MS powers down because all of the connections in the MS are in a sleep state [1]. For improving energy conservation efficiency, it is necessary to increase the amount of time an MS spends in an unavailable states. When there are several connections in sleep-mode, it is pivotal to consider how to make listening states between the connections intersect as many times as possible.

Earlier studies on power management, however, have mainly been carried out using the standard PSM [2], [5]. Another main interest regarding the standard PSM is how to enhance performance by finding the optimal values for operating parameters [3], [4], [6]. Importantly, previous studies have assumed that an MS has only one connection, and thus failed to solve the aforementioned situation. Consequently, this letter proposes a new Scheduled Power-Saving Mechanism (SPSM), to solve for conditions where an MS has two or more connections in sleep-mode. The basic idea of the SPSM is to schedule sleep-mode operations for connections in an MS. Specifically, this mechanism attempts to synchronize the initiation time of sleep-mode operation of a connection which will later transits into sleep-mode (defined as a *connection newly initiating sleep-mode*) to that of the connection already in sleep-mode (defined as a *connection already existing in sleep-mode*). The following sections explain how the SPSM operates within the applicable situations, and then performance evaluation results substantiate its effectiveness.

II. Scheduled Power-Saving Mechanism (SPSM)

Let us first observe the sleep-mode operations for the two connections in an MS, applying the standard PSM, as shown in Fig. 1. When one or both connections in an MS transit into normal operation (wake-mode), or the listening state, the MS is in an available state to communicate with the serving BS. Otherwise, it is in an unavailable state. From the figure, the total duration of the unavailable state of the MS is 14 units of time (U), and that of the available state of the MS is $16U$ during overall operation time ($30U$). However, if the listening states of both connections are able to intersect, the total duration of the available state of the MS can be reduced. So, for minimizing the total duration of the available state during sleep-mode operations, it is imperative to schedule

Manuscript received June 14, 2008. The associate editor coordinating the review of this letter and approving it for publication was J. Kim. This work was supported in part by the Korean Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MOST) (No. R11-2000-074-01001-0), and the MIC, Korea under the ITRC program (C-1090-0603-0036) supervised by IITA.

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Digital Object Identifier 10.1109/LCOMM.2008.081099

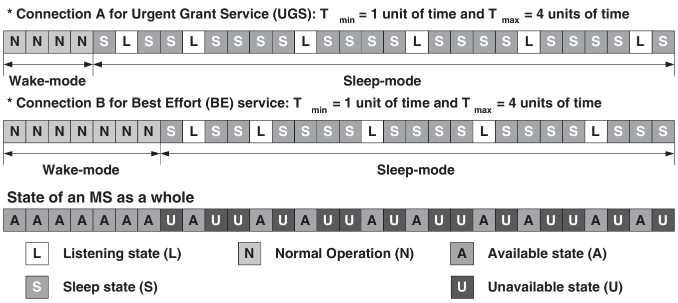

Fig. 1. Example of the behavior of an MS with sleep-mode operations for two connections under the standard PSM (the size of listening interval = 1 unit of time (U)) ([1], Figure 130a).

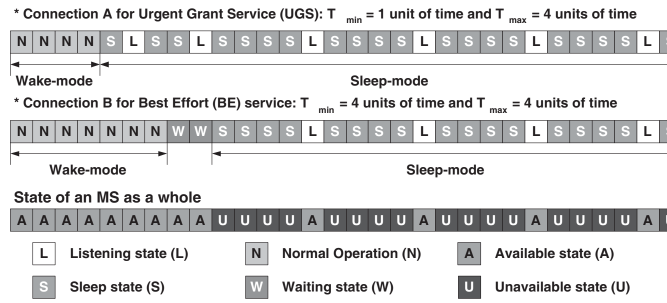

Fig. 2. Example of the behavior of an MS with sleep-mode operations for two connections under the new SPSM.

a sleep-mode operation for the connection newly initiating sleep-mode (CB) according to that of the connection already existing in sleep-mode (CA).

Fig. 2 illustrates the behavior of an MS with the sleep-mode operations for two connections under the SPSM. To synchronize the initiation time of sleep-mode operation for CB with that of the next sleep interval of CA (S^E_{nxt}), an MS first sends a sleep request message (MOB-SLP-REQ) before the transfer time of a sleep indication message (MOB-SLP-IND) for CA, which checks whether or not the serving BS wants to awaken the MS). This MOB-SLP-REQ message includes some information, such as T_{min} (= the next sleep interval of CA (T^E_{nxt})) and T_{max} (= T_{max} of CA (T^E_{max})). Then, the serving BS simultaneously sends a sleep response message (MOB-SLP-RSP) and a MOB-SLP-IND message to the MS. As a result of this mechanism, total duration of the available state can be reduced from $16U$ to $13U$. So, the SPSM can increase the battery life by increasing the unavailable time, during which the connections of the MS is in sleep-mode.

We have just explained a case with sleep-mode operations for two connections in an MS as an example of the effect of the SPSM, but the SPSM can also be applied in two or more connections in an MS. In reality, the applicability of this mechanism depends on the requirement of the QoS level for connections and its performance efficiency. Alg. 1 summarizes the operational mechanism of the SPSM to an applicable situation. First, if the QoS type of a connection newly initiating sleep-mode is UGS or a real time Polling Service (rtPS) (high QoS), the SPSM is not applied, because the connection could be affected by additional response delay time due to increasing T_{min} and the delayed initiation time of sleep-mode operation. Moreover, if there are several connections already in sleep-mode for high QoS, again the SPSM is not applied because SPSM may not significantly improve energy consumption efficiency due to the unscheduled connections for the high QoS. Thus, the SPSM is applied except in these two types of situations, where delay time degradation and low enhancement of power saving efficiency are expected. In the algorithm, the SPSM is applied in the case that a connection for low QoS newly initiates sleep-mode when there is only one connection for high QoS type or more than one connections for all low QoS types in sleep-mode. The remaining procedure in the algorithm is the same as we have just explained in the above paragraph and the standard PSM.

Algorithm 1 The operational mechanism of SPSM

Require: T^E_{nxt}, T^E_{max}, and S^E_{nxt}

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if the QoS type of the connection newly initiating sleep-mode is nrtPS or BE, then
    if only one connection for high QoS (UGS or rtPS) already exists in sleep-mode, or one or more connections for low QoS (nrtPS or BE) already exist, then
        Get T^E_nxt, T^E_max, and S^E_nxt.
        Wait until S^E_nxt before the next listening state of the connection already existing in sleep-mode.
        Send a sleep request message with T_min = T^E_nxt and T_max = T^E_max to the BS.
    else
        Send a sleep request message with T_min and T_max set by its application to the BS.
    end if
else
    Send a sleep request message with T_min and T_max set by its application to the BS.
end if
Receive a sleep response message from BS.
Transition to sleep-mode.
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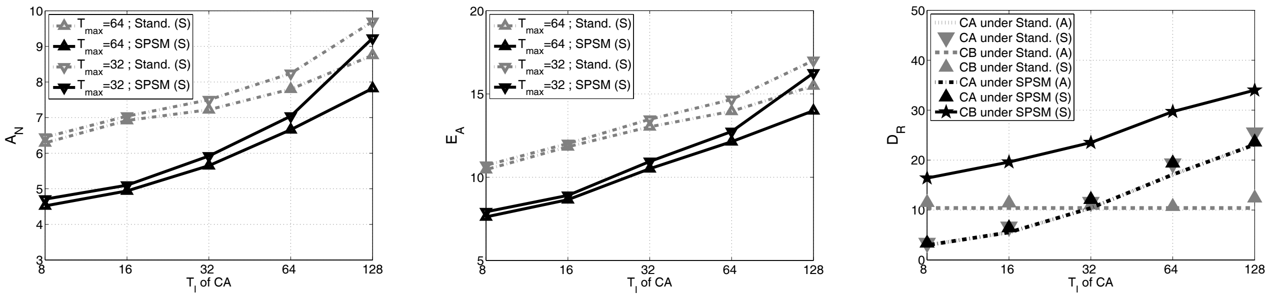
III. Numerical Analysis

This section shows an analytical model of sleep-mode operation for the response delay of BS initiations of awakening an MS. The arrivals of BS initiations of awakening follow a Poisson process with rate λ. The request period of BS initiations of awakening is exponentially distributed and set to the sleep time (the duration from the initiation time of sleep-mode of an MS to the awakening time). So, the average sleep time (T_I) is $\frac{1}{\lambda}$. It is assumed that L is a fixed length (=1U). The duration of the k^{th} sleep interval (T_k) [1] is shown as:

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

where M is the value that $T_k = T_{max}$. The duration of the k^{th} sleep cycle, which consists of a sleep interval and a listening interval, is given by:

$$C_k = T_k + L. \tag{2}$$



(a) The average available state of an MS in an overall sleep-mode operation (A_N)

(b) The average energy consumed by an MS in an overall sleep-mode operation (E_A) (mW)

(c) The average response delay time of BS initiations of awakening (D_R) (U)

Fig. 3. Performance comparison between the SPSM and the standard mechanism, with T_I of CB = $32U$ (T_I: the average sleep time, CA: Connection A, CB: Connection B, S: Simulation, A: Analysis).

The probability that there is no initiation of awakening during C_k (P_k) is obtained by:

$$P_k = e^{-\lambda C_k}, \ 1 \leq k \leq M. \tag{3}$$

Then, the probability that there is at least one initiation of awakening during C_k is 1-$e^{-\lambda C_k}$. Then, the probability that there is at least one initiation of awakening in the k^{th} sleep cycle during a sleep-mode operation is achieved by:

$$Pr_k = \sum_{j=0}^{k-1} P_j \cdot (1 - P_k) = e^{-\lambda \sum_{j=0}^{k-1} C_j}(1 - e^{-\lambda C_k}). \tag{4}$$

Since the arrival of initiations of awakening is independent of the sleep interval, the average response delay (D_R) for BS initiations of awakening is given by:

$$D_R \ = \ \sum_{k=1}^{\infty} Pr_k \cdot \frac{C_k}{2}. \tag{5}$$

IV. Performance Evaluation and Discussion

This section evaluates the performance of the SPSM with the following parameters: energy consumed during $1U$ of available state = 1.4mW, that of unavailable state = 0.045mW [7], and the size of the listening interval (L) = $1U$. Simulation results are obtained with the following assumptions: (i) there are one MS and one BS which communicates with each other [2]–[5], (ii) there are two connections in the MS: CA for high QoS and CB for low QoS, (iii) the request period of initiations of awakening in both connections is set to sleep time during one sleep-mode [2]–[5], and (iv) wake-mode is not considered as a part of the performance evaluation. [2]–[6].

Fig. 3 shows a performance comparison between the SPSM and the standard PSM. This evaluation is conducted under a fixed T_I of CB (=$32U$) and a varying T_I of CA (from 8 to $128U$). As expected, the SPSM produces a lower level of the average available state of an MS during sleep-mode operation compared with the standard PSM as shown in Fig. 3(a). As T_I of CA gets closer to $128U$, the effectiveness of the SPSM reduces because T_I is large enough to affect T_{max} [3]. We also observe that the two T_{max} sizes ($32U$ and $64U$) do not affect the available state differently, because T_{max} is dominant in response delay, but not energy consumption [3]. As a result of the resulting available state of an MS, the SPSM shows much better energy conservation efficiency than the standard PSM, and the pattern of enhancement is similar to the average available state as shown in Fig. 3(b). This implies that energy consumption is mainly affected by the average available state of the MS.

Fig. 3(c) shows the response delay performance. Since CA is affected by T_I but not SPSM, the response delay time of CA only increases according to the T_I. On the contrary, CB is affected by CA's operation due to the SPSM. Namely, the sleep-mode of CB operates with T_{min}, set to be the next sleep interval of CA, and T_{max}, equal to the T_{max} of CA. In SPSM operation, the delay time of CB is higher than that of CA using the SPSM. Since CB, a connection newly initiating sleep-mode, demands low QoS for delay insensitive services, the increased delay time is affordable.

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