Performance Evaluation and Optimization Guidelines for the Type II Power Saving Class of Mobile WiMAX

Dinh Thi Thuy Nga and Hyuk Lim

Abstract

In Mobile WiMAX (also known as IEEE802.16e), a standard power saving mechanism (PSM) that alternates between sleep and wake modes is adopted to extend the lifetime of mobile stations (MSs), but it simultaneously induces a medium access control (MAC) service data unit (SDU) response delay. The standard PSM defines three power saving classes (PSCs), among which Type I is based on a binary-exponential increase in the sleep window, and Type II is based on a constant sleep window. Over the years, most studies have mainly focused on PSC Type I, while only a few have considered Type II. This paper derives several analytical models of PSC Type II and evaluates the power consumption and MAC SDU response delay performance. Based on the derived models, an optimized power under delay-bound mechanism (OPDBM) is proposed to find the optimal initial sleep window parameter that minimizes the power consumption of an MS while satisfying a given MAC SDU response delay constraint. Both numerical analysis and simulation experiments show that the OPDBM effectively minimizes the power consumption of an MS while guaranteeing any imposed/required MAC SDU response delay constraint in a wide variety of environments.

Index Terms

IEEE802.16e, Mobile WiMAX, Type II PSC, power consumption, MAC SDU response delay

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I. INTRODUCTION

Recently, there has been renewed interest in energy conservation in information and communication technologies, where traffic has grown exponentially. Today, the energy costs incurred by large service providers are substantial [1] and constitute a large portion of their operational expenses in cases of mobile networks [2]. Traditionally, mobile communication networks were designed for maximum throughput and spectral efficiency, with less attention given to power consumption. In recent years, power efficiency has been considered an extremely important factor in the design of future wireless systems because future mobile communications demand much higher data rates, entailing significantly more power consumption. World Interoperability for Microwave Access (WiMAX), also known as the IEEE 802.16 standard, is a standard for enabling fixed and mobile convergence through broadband wireless access technology. As an enhancement of this standard, IEEE 802.16e (Mobile WiMAX) aims to reduce the energy consumed by a mobile station (MS) through power saving mechanisms (PSMs). These PSMs are especially important because an MS is generally powered by a limited battery supply.

Under a PSM, an MS repeatedly transits between sleep mode and wake mode to conserve energy. In sleep mode, an MS alternates between a sleep state and a listen state. In the sleep state, there is no communication between the MS and its serving base station (BS). This minimizes the MS's power consumption by decreasing its use of the BS's air interface resources. In the listen state, the MS checks for the arrival of a medium access control (MAC) service data unit (SDU) during the previous sleep state and can transmit a certain amount of data. Basically, the IEEE 802.16e standard specifies the PSM of the MAC protocol by defining three types of power saving classes (PSCs). PSCs are a group of connections that have a common demand/requirement [3], for providing specific QoS support. The Type I PSC is recommended for best effort (BE) and non-real time-variable rate (NRT-VR) services. The Type II PSC is recommended for delay-sensitive applications such as urgent grant service (UGS) and real time-variable rate (RT-VR) services. The Type III PSC is recommended for multicast connections and management operations [3]. Based on the PSM, an MS powers down its battery during the sleep state and powers up during the listen state [3]. Because the power consumed in the sleep state is much lower than that consumed in the listen state, it is desirable to reduce the duration of the listen states and increase the duration of the sleep states to reduce power consumption.

Although a PSM effectively extends the battery lifetime of MSs, it simultaneously causes an increase in the MAC SDU response delay. Note that that the delivery of a MAC SDU is delayed if it is destined for an MS in the sleep state. Thus, in addition to reducing power consumption, the MAC SDU response delay also has to be seriously considered because delay-sensitive applications have specific QoS requirements on latency and delay. For example, in IEEE 802.16m, the maximum state transition latency in the physical and MAC layers is recommended to be 100 ms or less [4], and the latency for voice and video conferencing services should not exceed 150 ms [5]. Moreover, the jitter for interactive-video should be no more than 30 ms [6]. Hence, the power consumption and MAC SDU response delay are two of the most important performance metrics for evaluating the PSM performance. In addition, it is essential to investigate the manner in which the sleep mode parameters affect the performance metrics to achieve the desired performance in various environments.

This study derives analytical models for evaluating power consumption and MAC SDU response delay of the Type II PSC. The paper then explains that a trade-off exists between power consumption and MAC SDU response delay because a longer sleep duration produces better power management but simultaneously causes an increase in the MAC SDU response delay. Based on this trade-off relationship, an optimized power under delay-bound mechanism (OPDBM) to minimize power consumption under a given MAC SDU response delay is proposed. The simulation results show that OPDBM effectively minimizes the power consumed in a wide variety of environments, in comparison with the standard PSM, which uses a fixed duration for the sleep state.

The remainder of this paper is organized as follows. Section II summarizes the previous work related to the Type II PSC. Section III describes the basic operation of the Type II PSC in the IEEE 802.16e standard. Section IV presents the analytical models for evaluating the performance of the Type II PSC. The proposed OPDBM is then described in Section V. Section VI presents the numerical results of extensive simulation experiments performed to evaluate the proposed analytical models and mechanism. Finally, Section VII concludes this paper.

II. Related Work

In the IEEE 802.16e standard, the Type I PSC for BE and NRT-VR services increases the sleep window size binary-exponentially from the initial sleep window (T_{min}) to the maximum sleep window (T_{max}) until there is a request for the MS to go into wake mode. Unlike the Type I PSC, the Type II PSC for delay-sensitive applications sets the sleep window at a constant value of T_{min}. This is because for the services supported by the Type II PSC, the reduction in the response delay is very critical [7]. In the Type III PSC, for multicast connections and management operations, MSs automatically transit from sleep mode to wake mode, skipping the listen state, because the services using the Type III PSC do not require a listen state [3].

Because of the importance of PSC applications in IEEE 802.16e systems, a significant amount of research has focused on evaluating the performance of the sleep mode operation and improving the power efficiency. Most of the studies, however, have focused on the Type I PSC. Its performance was extensively evaluated in [8]–[11], and various approaches for enhancing the power saving performance of PSMs have also been proposed in [12]–[14]. On the other hand, only a few studies have so far focused on the Type II PSC.

Cho *et al.* [15] proposed an adaptive initial sleep window scheme that is applicable to both the Type I and Type II PSCs of IEEE 802.16e. Their proposed scheme adaptively changes T_{min}, by keeping track of the burst inter-arrival time, to maximize the power saving without experiencing too much packet delay degradation. However, this scheme is only effective when the traffic volume is low; under heavy traffic, the scheme results in severe long delays. In another study [16], Chen *et al.* presented an energy conservation scheme, called maximum unavailability interval (MUI), to reduce power consumption by Type II PSC services by applying the Chinese remainder theorem. The MUI dynamically adjusts T_{min} to find the maximum unavailable interval during which the transceiver can be powered down. In addition, an algorithm to reduce the computational complexity when solving the Chinese remainder theorem is proposed. However, the authors did not seriously consider the MAC SDU delay, which is very important for real-time services supported by the Type II PSC. As an extension of this work, the authors further extended the MUI to a combination of Type I and Type II PSCs to achieve the maximum unavailability interval [17]. The proposed scheme aimed to reduce energy consumption and average packet response time of the Type I PSC by maximizing its unavailability interval. However, there was no evaluation of the delay performance in the Type II PSC. Furthermore, the authors in [18] presented a dynamic PSM that increases the unavailability interval when an MS uses two or more PSCs. Their proposed mechanism adjusts the sleep window and listen window of the Type I PSC or Type III PSC to those of the Type II PSC. By doing so, the MS can reduce the listening time and increase the unavailability interval; thus, power consumption in the MS is effectively reduced. From a historical review of Type II PSCs in the literature and to the best of our knowledge, no study has evaluated the performance of the Type II PSC with respect to sleep mode parameters such as T_{min}, which is done in this paper.

III. TYPE II POWER SAVING CLASSES IN MOBILE WIMAX

This section describes the Type II PSC and presents key ideas for enhancing its performance. The sleep mode parameters for the Type II PSC include the length of an initial sleep window (denoted by T_{min}), the length of a listening window (denoted by L), and the start frame number for the first sleep window.

Fig. 1 shows two example cases of sleep mode activation categorized by which station activates sleep mode. In case 1, an MS itself initiates sleep mode by sending a sleep request message, MOB_SLP-REQ, to its serving BS as shown in Fig. 1(a). After the BS receives MOB_SLP-REQ, the BS processes the control message and responds by sending a sleep response message, MOB_SLP-RSP, to the MS. Upon receiving the MOB_SLP-RSP message, the MS enters sleep mode at the frame specified by the start frame number for the first sleep window. As shown in Fig. 1(a), **all sleep windows are of the same size as T_{min}**. In case 2, sleep mode is activated by the BS, as shown in Fig. 1(b). In this case, the BS sends an unsolicited MOB_SLP-RSP message to the MS, initiating the MS's transition to sleep mode. Once it receives the MOB_SLP-RSP message, the MS transits to sleep mode [3].

Fig. 2 illustrates the initiating transition from sleep mode to wake mode. Either the MS or BS can initiate this transition. Sleep mode consists of several sleep cycles, where each sleep cycle comprises one sleep window and one listening window (i.e., $T_{min} + L$). When the MS has some protocol data units (PDUs) to transmit, it will transit to wake mode by sending a MOB_SLP-RSP or bandwidth request message to the BS while the MS is in sleep state, as shown in Fig. 2(a), or in listen state, as shown in Fig. 2(b), respectively. In addition, the BS may send an unsolicited MOB_SLP-RSP message or DL sleep control with an extended subheader to deactivate the PSC, as shown in Fig. 2(c) [3].

In contrast to the Type I PSC, where an MS cannot transmit or receive data during listen state, an MS in the Type II PSC can transmit a certain amount of data during the listen state. Let d be the number of MAC SDUs that arrive in one sleep cycle and μ be the holding rate

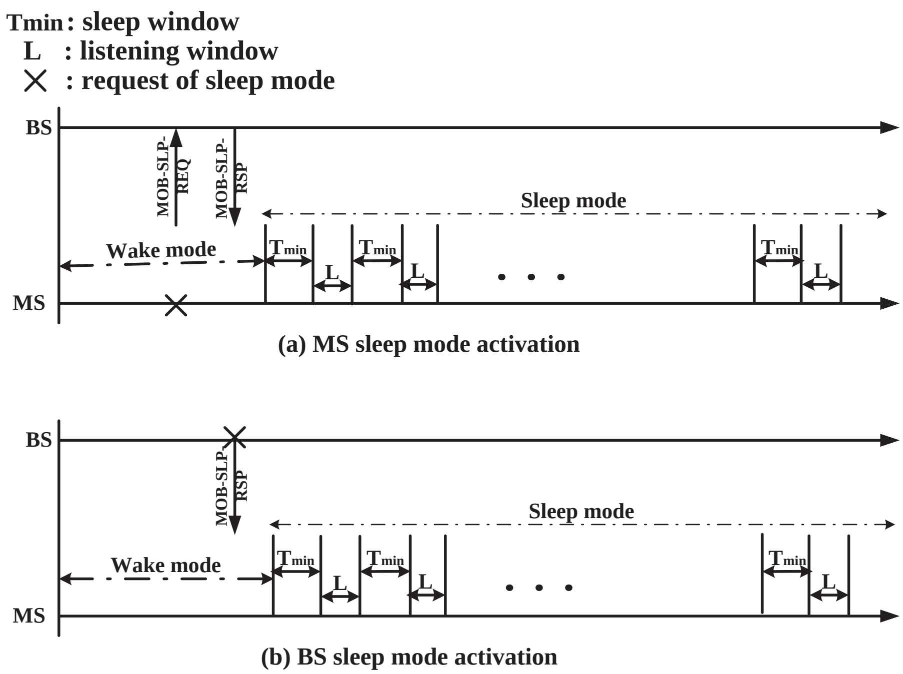

Fig. 1. Sleep mode activation by MS and BS

of incoming MAC SDUs. Assume that an MS remains in sleep mode if d does not exceed a maximum number N_0 that the MS can transmit during L. Then, $N_o = \lfloor \mu L \rfloor$. If $d > N_0$, the MS has to transit to wake mode. In addition, a MAC SDU arriving during a sleep state is put into the BS's queue, and will be forwarded to the MS when the MS moves from the sleep state to the listen state.

When the MS initiates its transition to wake-mode, there is no MAC SDU response delay, regardless of T_{min}. Therefore, in such situations a longer T_{min} helps reduce the power consumption to a great extent. However, in the case where the BS initiates the transition to wake mode, as in Fig. 2(c), a MAC SDU response delay will inevitably occur because the BS has to wait until the listen state of the MS before it can start transmitting the MAC SDUs to the MS. Thus, attention needs to be paid to power consumption as well as to reduction in the MAC SDU response delay.

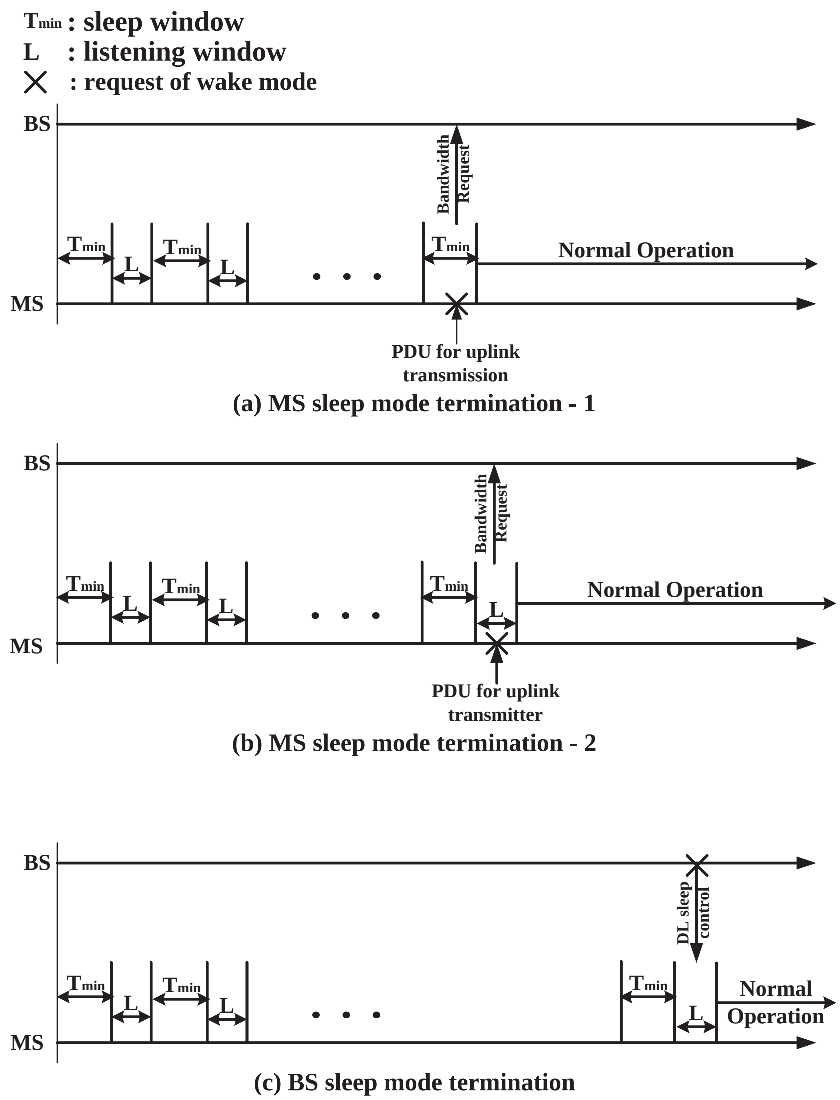

Fig. 2. Sleep mode termination by MS and BS

IV. ANALYTICAL MODELING

We next derive analytical models to predict the performance of the Type II PSC in Mobile WiMAX. In [19], it was reported that the arrival process for UGS, RT-VR, and NRT-VR traffic can be modeled as a Poisson process. In addition, traffic models following a Poisson distribution were suggested for performance evaluation in [20]. Here, we assume that the arrival of MAC SDUs at an MS follows a Poisson distribution with a rate of λ. Note that both λ and μ are measured by the number of MAC SDUs per frame. Let $p_i(t)$ denote the probability that there are exactly i MAC SDUs arriving during time t. Then, $p_i(t)$ is calculated as follows:

$$p_i\left(t\right) = \frac{\left(\lambda t\right)^i}{i!} e^{-\lambda t}. \tag{1}$$

Let P_{N_o} denote the probability that the number of incoming MAC SDUs during t does not exceed N_0. Then, P_{N_o} is determined such that

$$\begin{aligned} P_{N_o}\left(t\right) &= p_0\left(t\right) + p_1\left(t\right) + \cdots + p_{N_o-1}\left(t\right) + p_{N_o}\left(t\right) \\ &= e^{-\lambda t}\left(1 + \lambda t + \frac{\left(\lambda t\right)^2}{2!} + \cdots + \frac{\left(\lambda t\right)^{N_o}}{N_o!}\right). \end{aligned} \tag{2}$$

Note that an MS wakes up after n sleep cycles if and only if there are no more than N_0 incoming MAC SDUs in each of the $(n-1)$ previous sleep cycles and at least (N_0+1) MAC SDUs in the n-th sleep cycle. Let $P(n)$ denote the probability of this event. Then, $P(n)$ is given by

$$\begin{aligned} P\left(n\right) &= \text{Prob}\left(\begin{array}{l} N_o \geq \text{ \# of MAC SDUs in sleep cycles of } [1, \cdots, n-1]; \\ N_o < \text{\# of MAC SDUs in } n\text{th sleep cycle} \end{array}\right) \\ &= \text{Prob}\left(N_o \geq \text{ \# of MAC SDUs in sleep cycles of } [1, \cdots, n-1]\right) \\ &\quad \times \text{Prob}\left(N_o < \text{\# of MAC SDUs in } n\text{th sleep cycle}\right) \\ &= P_{N_o}^{n-1}(C)\ (1 - P_{N_o}(C)), \end{aligned}$$

where C is the duration of a sleep cycle, and $C = T_{min} + L$. Note that T_{min} and L are measured in terms of the number of frames in the standards.

A. Sleep Time Model

Let N_S be the number of sleep cycles that an MS spends in sleep mode. Throughout this paper, the notation $E[.]$ is used to stand for an expectation or mean function. Thus, the expectation of N_S is

$$E\left[N_S\right] = \sum_{n=1}^{\infty} nP\left(n\right). \tag{3}$$

From (3), it can be inferred that $E\left[N_S\right] > 1$ because $\sum\limits_{n=1}^{\infty} P\left(n\right) = 1$. $E\left[N_S\right]$ can also be rewritten as

$$E\left[N_S\right] = 1 - P_{N_o}\left(C\right) + \sum_{i=1}^{\infty} P_{N_o}^{i}\left(C\right)\left(1 - P_{N_o}\left(C\right)\right)\left(i+1\right). \tag{4}$$

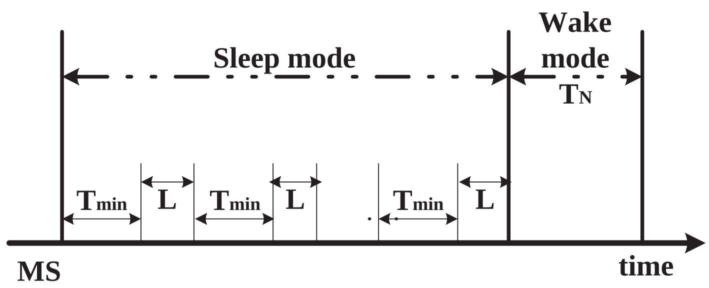

Fig. 3. Complete sleep mode operation cycle

Because $\lim_{T_{min}\to\infty} P_{N_o}(C) = 0$, $E[N_S]$ goes to 1 as T_{min} approaches infinity. This means that as T_{min} increases, an MS goes to wake mode only after one sleep cycle.

Let T_S denote the time the MS is in sleep mode. Then, the expectation of T_S is given by

$$E[T_S] = \sum_{n=1}^{\infty} nP(n)(T_{min} + L) = E[N_S](T_{min} + L). \tag{5}$$

From (5), it can be inferred that $E[T_S] > (T_{min} + L)$. This implies that an MS, on average, stays in sleep mode for a duration longer than one sleep cycle before it transits to wake mode.

B. Power Consumption Model

When an MS transits from sleep to wake mode, it spends a certain amount of time T_N to process all the MAC SDUs that arrived during its previous sleep mode, as shown in Fig. 3. Note that while processing those MAC SDUs, new MAC SDUs may arrive; hence, T_N should also include the time for processing all the newly arriving MAC SDUs. As a result, the total time T_{total} in sleep and wake modes can be obtained as

$$E[T_{total}] = E[T_S] + E[T_N]. \tag{6}$$

Let $E[N_{remain}]$ and $E[N_{new}]$ be the mean numbers of outstanding and newly arriving MAC SDUs, respectively. Then, T_N is calculated as follows

$$E[T_N] = \frac{1}{\mu}(E[N_{remain}] + E[N_{new}]), \tag{7}$$

where

$$E[N_{remain}] = \sum_{i=1}^{\infty} ip_{N_o+i}(C).$$

The number of newly arriving MAC SDUs during T_N is calculated using Little's Law [21]:

$$E\left[N_{new}\right] = \lambda E\left[T_N\right]. \tag{8}$$

By (7) and (8), we have

$$E\left[T_N\right] = \frac{E\left[N_{remain}\right]}{\mu - \lambda} = \frac{\sum_{i=1}^{\infty} i p_{N_o+i}\left(C\right)}{\mu - \lambda}. \tag{9}$$

By putting (5) and (9) into (6), $E[N_{total}]$ is determined as

$$E\left[T_{total}\right] = E\left[T_S\right] + \frac{E\left[N_{remain}\right]}{\mu - \lambda} = E\left[N_S\right]\left(T_{min} + L\right) + \frac{\sum_{i=1}^{\infty} i p_{N_o+i}\left(C\right)}{\mu - \lambda}. \tag{10}$$

We first calculate the energy that an MS consumes in sleep mode. Let P_S and P_L denote the power consumed by an MS in the sleep and listen states, respectively. Because an MS in the listen state operates as it does in wake mode, P_L is equal to the power consumed in wake mode. Each sleep cycle includes one switch from the sleep to listen state and another switch from the listen to sleep state. Let E_s denote the energy that an MS consumes in sleep mode. Then, the expectation of E_s is given by

$$E\left[E_s\right] = E\left[N_S\right]\left(T_{min}P_S + LP_L + E_{switch-on} + E_{switch-off}\right), \tag{11}$$

where $E_{switch-on}$ and $E_{switch-off}$ are the energy consumed for switching from the sleep to listen state and that for switching from the listen to sleep state, respectively. Let E_{total} denote the total energy that an MS consumes in sleep and wake modes to transmit all the MAC SDUs. Then, E_{total} is

$$E\left[E_{total}\right] = E\left[E_s\right] + E\left[T_N\right] \cdot P_L. \tag{12}$$

By combining (12) with (10), the average power consumption P_{avg} of a Type II PSC MS is as follows:

$$P_{avg} = \frac{E\left[E_{total}\right]}{E\left[T_{total}\right]} = \frac{E\left[E_s\right] + E\left[T_N\right] \cdot P_L}{E\left[T_S\right] + E\left[T_N\right]}, \tag{13}$$

where $E[T_S]$, $E[T_N]$, and $E[E_s]$ are calculated by (5), (9), and (11), respectively. Note that the numerator in (13) is the energy that an MS consumes in sleep mode and wake mode to transmit all the MAC SDUs, and the denominator is the time elapsed in the sleep and wake modes. In (13), P_{avg} is given as a function of T_{min}, and in Section VI, we will numerically show that P_{avg} decreases as T_{min} increases.

C. MAC SDU Response Delay Model

Let D be the time delay experienced by a MAC SDU, from the time it arrives during an MS' sleep mode until it receives a response from the MS. Hence, D includes the waiting time W for the MS to transit from the sleep to listen state and the service time R required for the MS to process all the previous MAC SDUs. Then, the expectation of D is $E[D]$ = $E[W]$ + $E[R]$.

To calculate $E[W]$, T_{min} is divided into K intervals with equal duration τ. Then, at the k-th interval, the MAC SDU waiting time for the MS to transit from the sleep to listen state is $W_k = T_{min} - k\tau$. Hence, the expectation of W is

$$E\left[W_k\right] = \frac{1}{K}\sum_{k=1}^{K} W_k = \frac{1}{K}\sum_{k=1}^{K}\left(T_{min} - k\tau\right) = \frac{T_{min}}{2} - \frac{T_{min}}{2K}. \tag{14}$$

Because $\lim\limits_{K\to\infty} \frac{T_{min}}{2K} = 0$, $E[W]$ is given by

$$E\left[W\right] = \frac{T_{min}}{2}. \tag{15}$$

Moreover, the service time R needs to be considered when at least one MAC SDU arrives during T_{min}. Suppose that there are i MAC SDUs arriving during T_{min} and $i > 1$. For the j-th MAC SDU with $1 \leq j \leq i$, the time that this MAC SDU has to wait until it is served is $(j-1)\frac{1}{\mu}$. Therefore, for i MAC SDUs arriving during T_{min}, the expected time that each MAC SDU has to wait is $(i-1)\frac{1}{2\mu}$. Then, $E[R]$ is given by

$$E\left[R\right] = \sum_{i=1}^{\infty} \frac{i-1}{2\mu} p_i\left(T_{min}\right) = \frac{e^{-\lambda T_{min}}}{2\mu} \sum_{i=1}^{\infty} \frac{(i-1)\left(\lambda T_{min}\right)^i}{i!}.$$

If we let $x = \lambda T_{min} > 0$, $E\left[R\right]$ can be rewritten as

$$E\left[R\right] = \frac{1}{2\mu} \cdot \frac{x + e^{-x} - 1}{1 - e^{-x}} = \frac{1}{2\mu} \cdot \left(\frac{x}{1 - e^{-x}} - 1\right). \tag{16}$$

Let $f\left(x\right) = \frac{x}{1-e^{-x}}$, with $x \geq 0$. Then, $f'(x)$ = $\frac{1-e^{-x}-xe^{-x}}{(1-e^{-x})^2}$. In addition, let $g\left(x\right) = 1 - e^{-x} - xe^{-x}$. Then, $g'(x)$ = $xe^{-x} > 0$. Therefore, $g\left(x\right) \geq g\left(0\right) = 0$; as a result, $f'(x)$= $\frac{g(x)}{(1-e^{-x})^2} \geq 0$. This implies that $f(x)$ is an increasing function of x, and thus, $E[R]$ is an increasing function of both λ and T_{min}. By combining (15) and (16), the response delay of a MAC SDU arriving while the MS is in the sleep state is

$$E\left[D\right] = \frac{T_{min}}{2} + \frac{1}{2\mu} \cdot \left(\frac{\lambda T_{min}}{1 - e^{-\lambda T_{min}}} - 1\right). \tag{17}$$

Interestingly, $E[D]$ does not depend on N_0, which is the capacity at which an MS can transmit during its listen state. In addition, it can be seen from (17) that $E[D]$ is an increasing function of both λ and T_{min}. This also means that an increase in either T_{min} or λ will result in a poor delay performance.

V. OPTIMIZED POWER UNDER DELAY-BOUND MECHANISM

In this paper, the goal of PSMs is to minimize power consumption in MSs under a given MAC SDU response delay constraint. As inferred from the analytical results in Section IV, there is a trade-off between power consumption and MAC SDU response delay. In other words, an increase in T_{min} results in less power consumption, but a longer MAC SDU response delay. Succinctly, the optimal T_{min} that gives the lowest power consumption can be found by gradually increasing the value of T_{min} as long as the delay performance is guaranteed. In this paper, we propose the "optimized power under delay-bound mechanism" (OPDBM), to determine the optimum T_{min} for the Type II PSC in Mobile WiMAX. This mechanism can be regarded as a policy optimization problem for dynamic power management for minimizing power consumption in MSs, while ensuring that the MAC SDU response delay remains lower than the required bound [22].

In the IEEE 802.16e standard [3], L has a fixed duration. Furthermore, because λ and μ depend on the customers and server behavior, which are not controllable parameters, for simplicity, they are assumed to be already known. Let D_{giv} (number of frames) denote the MAC SDU response delay constraint. Then, from a given parameter set of D_{giv}, λ, μ, and L, we compute the optimal T_{min} that can achieve the lowest power consumption. The power consumption minimization based on the MAC SDU delay constraint is formulated as follows:

$$\begin{aligned} \text{minimize} \quad & P_{avg} \\ \text{subject to} \quad & E[D] \leq D_{giv} \\ & T_{min} \in Z^{+}. \end{aligned} \tag{18}$$

One may solve this integer programming problem using a brute-force search in a large range of T_{min}. Instead, we reduce the search space of T_{min} by exploiting the analytical models derived in Section IV to make the search operation more tractable. By (17), the first constraint for $E[D]$

Algorithm 1 A simple pseudo-code of the proposed OPDBM

Require: D_{giv}, λ, μ, and L.

Assign $T^*_{min} = (2D_{giv} - 1)$ and $P^* = \infty$
for $T_{min} = T^*_{min}$ to 1 **do**
  Calculate $E[D]$ using (17)
  if $E[D] \leq D_{giv}$ **then**
    Calculate P_{avg} using (13)
    if $P_{avg} \leq P^*$ **then**
      $P^* = P_{avg}$ and $T^*_{min} = T_{min}$
    end if
  end if
end for

is rewritten as

$$E\left[D\right] = \frac{T_{min}}{2} + \frac{1}{2\mu} \cdot \left(\frac{\lambda T_{min}}{1 - e^{-\lambda T_{min}}} - 1\right) \leq D_{giv}. \tag{19}$$

It is obvious from (19) that $T_{min} < 2D_{giv}$ if the first constraint is satisfied. Note that if $T_{min} = 2D_{giv}$, then, $E\left[D\right]$ becomes greater than D_{giv}. Therefore, T_{min} must satisfy:

$$1 \leq T_{min} < 2D_{giv}.$$

This range implies that the optimal solution for T_{min} belongs to the set of $\mathcal{X} = \{1, \cdots, (2D_{giv} - 1)\}$. In this formulation, the second constraint for T_{min} is imposed to keep the compatibility with the WiMAX standards.

The optimization problem in (18) is solved by searching the significantly reduced space of $\mathcal{X}$, as shown in Algorithm 1. Note that this search space is considerably more limited than the original one for T_{min}; thus, the values that achieve the minimum P_{avg} as the optimal solution T_{min} can be efficiently selected. Therefore, the proposed OPDBM is optimal in terms of power consumption and always converges if there is a solution that satisfies the delay constraint. This simplified version of Algorithm 1 can be further optimized by exiting the loops based on the finding that P_{avg} is inversely proportional to T_{min}. Note that these optimal solutions can be computed in advance and tabulated for various values of D_{giv}, λ, μ, and L.

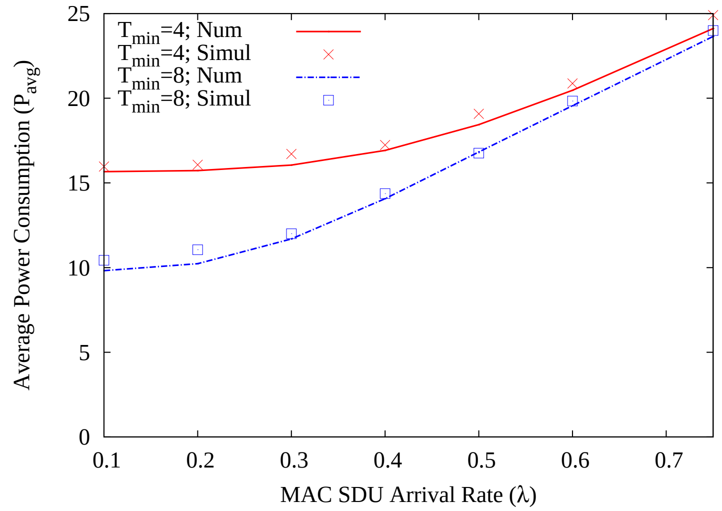

Fig. 4. Average power consumption with respect to λ

VI. SIMULATION RESULTS

A. Validation of Numerical Model

First, we validate our proposed numerical models using computer simulations based on the following parameters: P_S = 1 mW, P_L = 30 mW, and $E_{switch-on}$ = $E_{switch-off}$ = 15 mJ. μ is normalized to 1, and λ is varied from 0 to 1. The simulations run for 1,000,000 time units (frames), and the results are the mean values from 100 different runs with different random seed values. Note that if the MAC SDU arrival rate exceeds the MAC SDU service rate (i.e., $\lambda > \mu$), the queuing delay will grow infinitely, and the MS will never go into sleep mode.

Fig. 4 presents the average power consumption P_{avg} with respect to λ for different T_{min} when L = 2 (frames). As shown in the figure, P_{avg} increases rapidly as λ increases. It can be further noted that an MS sleeps longer when λ is small. However, as λ increases, the MS transits from sleep mode to wake mode more frequently, and because the power consumed in a listen state is much higher than that consumed in a sleep state, the larger λ results in a larger P_{avg}. Fig. 5 presents the effects of T_{min} on P_{avg} for different λ with L = 2. This figure shows that P_{avg} decreases with respect to T_{min} because a larger T_{min} results in a longer duration it takes for an MS to sleep. Because the power consumed by an MS in the sleep state is much lower than that consumed in the listen or wake mode, the larger T_{min} results in a lower P_{avg}. However,

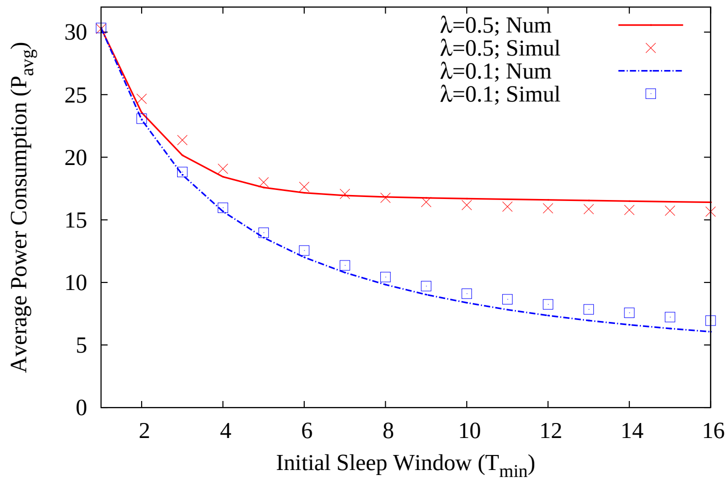

Fig. 5. Average power consumption with respect to T_{min}

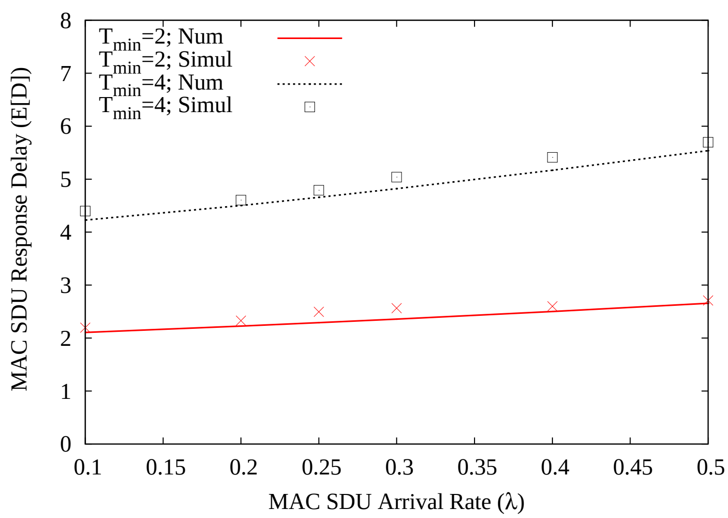

Fig. 6. MAC SDU response delay with respect to λ

the larger T_{min} causes a poor MAC SDU response delay performance. This implies that there is a trade-off between the power consumption and MAC SDU response delay performances. Therefore, they cannot be simultaneously improved.

Fig. 6 presents the average MAC SDU response delay with respect to λ, where it can be seen that $E[D]$ increases as λ increases. This is because, when λ increases, more MAC SDUs arrive during T_{min}, and the packets that arrive after the MS goes into the sleep state suffer a delay

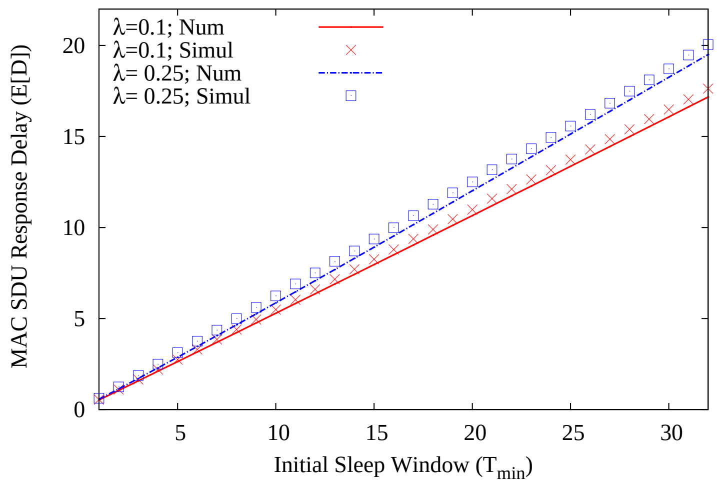

Fig. 7. MAC SDU response delay with respect to T_{min}

increase. As shown in Fig. 7, when T_{min} increases, $E[D]$ also increases because an MS sleeps for a longer time. In the figure, we also observe that $E[D]$ is linearly proportional to T_{min}. This is because the first term in (17), which is linearly proportional to T_{min}, is a dominant factor compared to the second term. From Figs. 6 and 7, it can be seen that $E[D]$ is also proportional to both λ and T_{min}, which is in accordance with the analytical results presented in Section IV-C.

B. OPDBM Performance Evaluation

We first evaluate the amount of power consumed to ensure that the MAC SDU delay constraint is satisfied. Then, we compare the power consumption performances of the OPDBM and the original PSM in the Type II PSC under different simulation scenarios. Here, L is set to 2 (frames) and N_0 is 2 (number of MAC SDUs).

Fig. 8 presents the average power consumed by the OPDBM and the standard PSM with different T_{min}, with respect to the MAC SDU response delay constraint D_{giv}. Here, λ is fixed at 0.1. In this figure, the black dots represent the power consumptions of the original PSM for T_{min}'s that make the MAC SDU delay equal to or lower than the corresponding D_{giv} on the x-axis. In all the cases, the OPDBM successfully selects the T_{min} that results in the lowest power consumption. For D_{giv} = 1, the standard PSM needs to set T_{min} at 3, but the value of T_{min} is too small for the case where $D_{giv} = 8$. If T_{min} = 3 for D_{giv} = 8, the power consumption of the

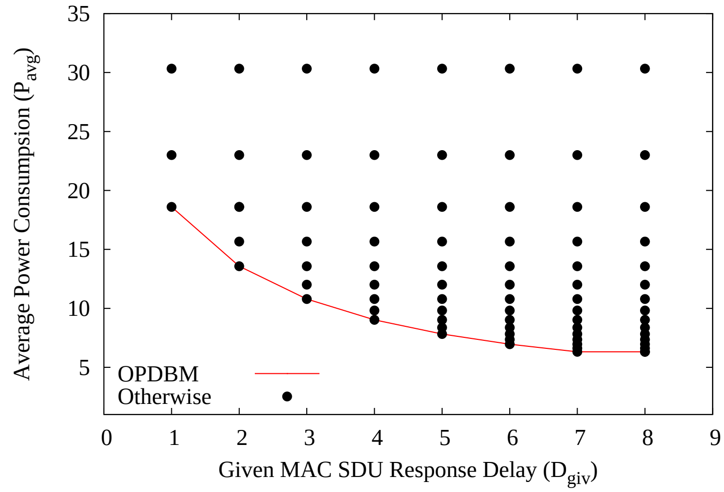

Fig. 8. Average power consumption with respect to D_{giv}

standard PSM is 19, whereas the OPDBM consumption is 6, representing a power consumption reduction of up to 68%. As explained in Section V, based on the analytical models, OPDBM first evaluates the MAC SDU response delay for all the possible values of T_{min} belonging to the set of $\mathcal{X}$, and then selects the one that gives the lowest P_{avg} from all the values that satisfy the MAC SDU delay constraint. Because the set of $\mathcal{X}$ is limited, the algorithm of the OPDBM always converges. For the original PSM of the Type II PSC, if T_{min} is not properly chosen, the power consumption could become significantly larger than the optimal, especially when D_{giv} is large.

Fig. 9 shows that the MAC SDU delay obtained by OPDBM satisfies the delay constraint. As seen in the figure, the points formed by D_{giv} on the x-axis and $E[D]$ obtained by OPDBM on the y-axis lie below the bisector of the first quarter angle. This means that $E[D]$ does not exceed D_{giv}. The results in Figs. 8 and 9 imply that OPDBM not only minimizes the power consumption but also guarantees the MAC SDU response delay.

Fig. 10 shows the power consumption of the OPDBM and the standard PSM with different T_{min} with respect to λ. Here, the MAC SDU response delay constraint is 5, (i.e., D_{giv} = 5). Regardless of λ, OPDBM achieves the lowest P_{avg}, while that of the standard PSM depends on the selection of T_{min}. For λ = 0.9, the standard PSM should set T_{min} at 5 to satisfy the delay constraint. However, a fixed value of T_{min} results in a power consumption of 14 for λ = 0.1,

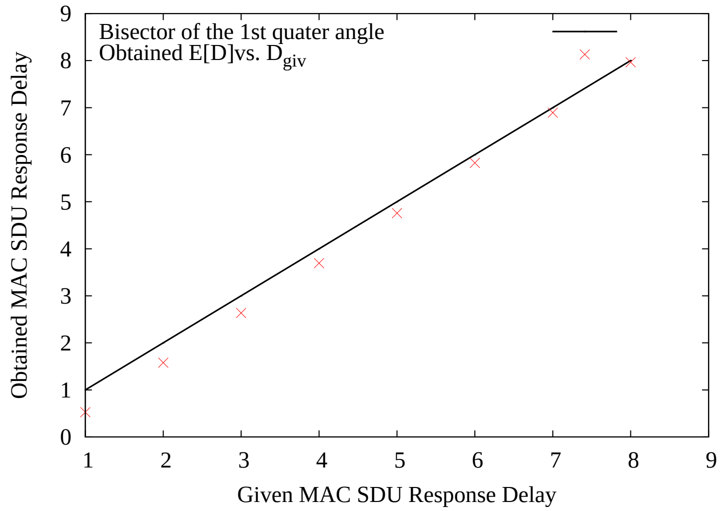

Fig. 9. MAC SDU response delay obtained by OPDBM with respect to D_{giv}

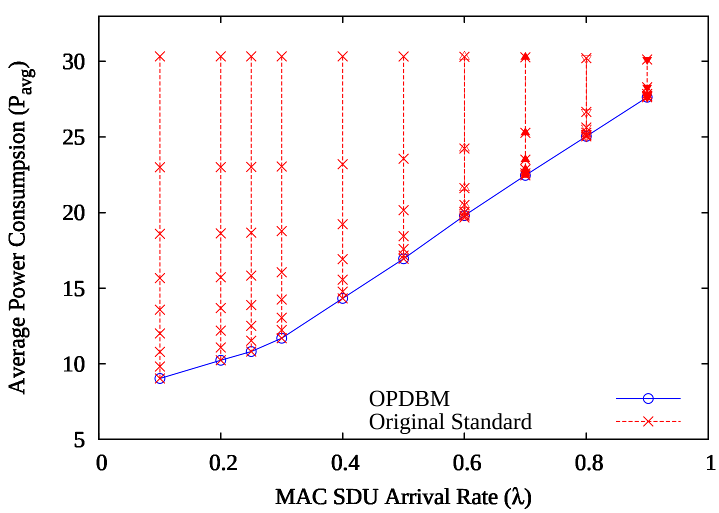

Fig. 10. Average power consumption with respect to λ

while OPDBM achieves a power consumption of 9. Therefore, the OPDBM reduces the power consumption by 35%, in comparison with the standard PSM, thereby significantly extending the battery lifetime of the MS. As shown in Fig. 4, as λ increases, the minimum P_{avg} obtained when the delay constraint is satisfied also increases.

Fig. 11 shows that the MAC SDU response delay obtained by the OPDBM does not exceed D_{giv} as λ increases. This is because OPDBM always chooses the T_{min} that makes $E[D]$ equal

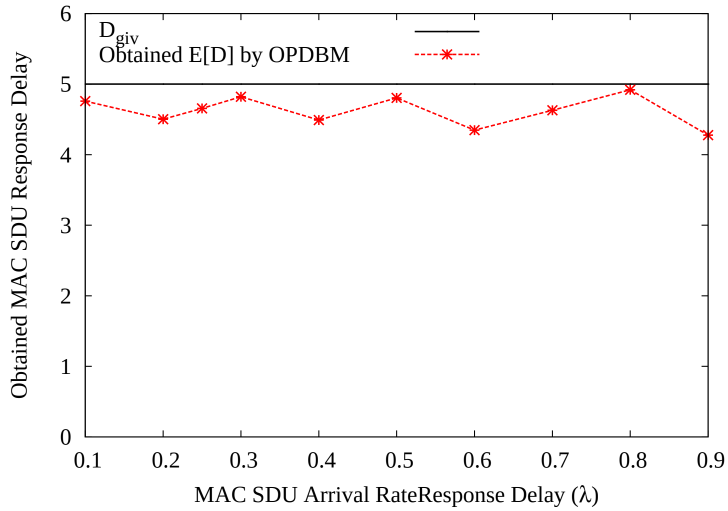

Fig. 11. MAC SDU response delay obtained by OPDBM with respect to λ

to or lower than D_{giv}. It can also be observed in Fig. 11 that $E[D]$ fluctuates. For example, the first point and the next three points show the $E[D]$ values when T_{min} is equal to 9 and 8, respectively. When T_{min} decreases from 9 to 8, $E[D]$ decreases in the same manner shown in Fig. 6. However, when T_{min} is fixed at 8, $E[D]$ is seen to increase as λ increases, as discussed in Section IV-C. For the other points, we obtain similar results, wherein $E[D]$ increases as λ increases for the same T_{min} and $E[D]$ increases when T_{min} increases.

VII. CONCLUSION

We evaluated the performance of the Type II PSC in the IEEE 802.16e standard by deriving analytical models for the sleep cycles, sleep time, consumed power of an MS, and MAC SDU response delay. We showed that these performance metrics are functions of T_{min}, and they are significantly affected by T_{min}. Further, we demonstrated that a trade-off exists between power consumption and MAC SDU response delay, which are the two most important performance metrics for the Type II PSC.

Next, we proposed optimal power saving under the delay-bound mechanism (OPDBM), which minimizes the power consumption under a given MAC SDU response delay. A set of T_{min} values that can satisfy the MAC SDU condition were first identified via numerical analysis. Then, the one that consumed the least power was chosen as the optimal T_{min}. Therefore, the proposed

OPDBM is optimal in terms of power consumption and always converges if there is a feasible solution that satisfies the delay constraint. The extensive simulations showed that the proposed OPDBM achieved a power consumption reduction of up to 68% and 35%, when the MAC SDU response delay constraint varied from 1 to 8, and the arrival rate of MAC SDU varied from 0.1 to 0.9, respectively. The analysis and method presented in this paper would provide a potential guideline for efficiently managing power consumption and MAC SDU response delay for the Type II PSC in IEEE 802.16e systems.

ACKNOWLEDGEMENT

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