Power Saving Mechanism with Delay Bound for Mobile WiMAX Systems

Dinh Thi Thuy Nga and Hyuk Lim

Abstract

In Mobile WiMAX, the power saving mechanism (PSM), which operates alternately in sleep and awake modes, works to extend the lifetime of mobile stations (MSs), though it concurrently induces a medium access control (MAC) service data unit (SDU) response delay. In this paper, we derive the analytical models for two of the most important performance metrics: the average power consumption and the average MAC SDU response delay of an MS in sleep mode. These metrics are given as a function of the sleep mode system parameters: initial sleep window T_{min} and final sleep window T_{max}. Based on these models, we show that a tradeoff relationship exists between them. We then propose an optimized power-saving mechanism (OPSM) that jointly determines the optimal T_{min} and T_{max} in order to minimize the power consumption under a given MAC SDU response delay constraint. Through both numerical analyses and subsequent simulations, we show that the OPSM effectively minimizes power consumption of an MS in its sleep mode while guaranteeing the MAC SDU response delay constraint.

Index Terms

Mobile WiMAX, sleep-mode operation, power consumption, MAC SDU response delay.

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I. INTRODUCTION

Over the past few decades, developments in the content available on the Internet and its resultant usage have led to increasing demands for higher speed ubiquitous internet access. To meet these demands, broadband wireless access (BWA) is considered a promising technology, which aims to supply a broad bandwidth at low cost for residential and business applications. The World Interoperability for Microwave Access (WiMAX) [1] standard enables fixed and mobile convergence through BWA technology and a flexible network architecture. As an enhancement of this standard, IEEE 802.16e (Mobile WiMAX) [1] has targeted the development of service provisioning to mobile stations (MSs). It includes mobility components and defines both physical and medium access control (MAC) layers to combine fixed and mobile operations in licensed bands; for mobility support, a power saving mechanism (PSM) is extremely important because MSs are generally powered by a limited battery supply.

In a PSM, an MS alternately operates in sleep and awake modes in order to reduce the overall power consumption. A sleep mode is the state in which an MS conducts pre-negotiated periods of absence from the air interface of its serving base station (BS). When the MS is in sleep mode, there is no communication between the MS and its serving BS. In contrast, the MS in awake mode actively checks whether or not there has been a frame addressed to it during its preceding sleep time. Because the MS powers down its battery during sleep mode and powers up in awake mode [1], the power consumed per time unit during sleep mode is much lower than in awake mode; therefore, how to effectively reduce the duration of the awake mode is a key factor in saving energy. In general, the durations of sleep and awake modes are determined by sleep mode parameters such as *initial sleep window* T_{min} and *final sleep window* T_{max} [2]–[4], and thus determining a suitable value for T_{min} and T_{max} is essential in the WiMAX PSM.

In the IEEE 802.16e standard [1], three types of power saving class (PSC) are defined. Here, we consider a PSC Type I, which is recommended for the best effort (BE) and non-real-time variable rate (NRT-VR) activities. In terms of PSMs for PSC Type I, performance evaluations were previously carried out in [2]–[6]; we will provide a summary of existing works in Section II. In brief, this paper first derives analytical models for evaluating the power consumption and MAC SDU response delays of an MS in sleep mode, given as a function of T_{min} and T_{max}. Unlike the model for power consumption in [2], we derive the average power consumption per time unit of an MS in its sleep mode, which is shown to be inversely proportional to sleep window sizes, rather than using the average energy consumption as a performance metric. In addition, our simple model for a MAC SDU response delay makes it easy to evaluate how much the delay time depends on the sleep window size. Second, we formulate the problem of how to optimize the power consumption under a given MAC SDU response delay. Based on this formulation, we then propose an optimized power-saving mechanism (OPSM) that jointly determines the optimal T_{min} and T_{max} in order to minimize the power consumption under a given MAC SDU response delay constraint. The proposed method for this mechanism is novel and more secure than in our previous studies [7], [8]. Next, through both numerical analyses and simulations, we show that the OPSM effectively minimizes the power consumption of an MS in its sleep mode, while guaranteeing the MAC SDU response delay constraint.

The remainder of this paper is organized as follows. In Section II, we present previous works related to WiMAX and Mobile WiMAX standards. Next, Section III describes the basic operation of a PSM in the IEEE 802.16e standard, and Section IV presents our numerical models for evaluating the performance of IEEE 802.16e systems. The proposed OPSM is then described in Section V, and Section VI presents the simulation evaluations for the analytical models and the proposed mechanism. Finally, Section VII concludes this paper.

II. RELATED WORK

A. Background in Mobile WiMAX

Various aspects of WiMAX such as scheduling, handover, cognitive radio, and transmitting multimedia streaming have been widely studied. For example, in [9], a cognitive WiMAX architecture was proposed for applying cognitive radio technology to Mobile WiMAX networks in order to increase capacity and simplify network operations. In this architecture, power control is employed to increase frequency reuse, in conjunction with spectrum sensing. The problem of multiuser resource management in multihop cognitive radio networks for delay-sensitive applications was then presented in [10]. The authors considered the delay and overhead for exchanging network information over multihop cognitive radio networks, and proposed a resource-management algorithm that allows network nodes to exchange information in a distributed manner. More recently, Yeh *et al.* [11] proposed a fast intra-network and cross-layer handover

(FINCH) for intra domain mobility management in order to support fast and efficient handovers in Mobile WiMAX.

Scheduling in wireless networks in Mobile WiMAX has been extensively studied. For instance, Chakchai *et al.* presented a survey of recently proposed scheduling algorithms [12]. Then, Zhou [13] considered the problem of video streaming over multichannel multi-radio multihop wireless networks, and developed fully distributed scheduling schemes based on the goal of minimizing video distortion and achieving certain fairness.

In addition to these topics, multimedia streaming over wireless networks including WiMAX was investigated in [14]–[16]. In order to support multimedia applications over heterogeneous networks, Zhou *et al.* [14] proposed efficient context-aware middleware for multimedia services by combining an adaptive service provisioning middleware framework with a context-aware multimedia middleware framework. In [15], the authors discussed challenges and possible solutions for transmitting MPEG video streams over WiMAX networks, and proposed a solution for enhancing the performance for streaming MPEG video. Media streaming with network diversity was also discussed in [16], in which the authors presented an overview of distributed streaming solutions that profit from network diversity in order to improve the quality of multimedia applications.

B. Power saving mechanisms in mobile WiMAX

Seo *et al.* [5] investigated the queuing behavior of sleep mode in terms of the dropping probability and mean wait time of packets in the BS queue. Similarly, Han and Choi numerically analyzed the PSM using a Markov chain and derived the packet delay and energy consumption for each sleep, listening, and waking-up state [6]. Zhang and Fujise [3] then studied sleep mode operation and analyzed its performance for uplink and downlink traffic cases. And Xiao [2] evaluated the performance of the IEEE 802.16e standard PSM in terms of average energy consumption and MAC SDU response delay for an MS in sleep mode. Unlike this model, however, in this study we derive the average power consumption per time unit of an MS in sleep mode, which is subsequently shown to be inversely proportional to the sleep window size, rather than using the average energy consumption as a performance metric.

In addition to the efforts undertaken regarding performance analysis, various approaches for enhancing the power saving performance of PSMs have also been proposed. In [4], [17], the sleep window size was adjusted by considering the state of the previous sleep-mode operation under light traffic conditions. Unfortunately, these works resulted in a degradation of the delay performance, though the power consumption was significantly improved compared to the original PSM [4], [17]. In [17], the initial sleep window of the next sleep mode was updated periodically using half of the last sleep window from the previous sleep-mode operation. However, this mechanism was only effective when the traffic volume was low; under heavy traffic conditions, it resulted in a severely long MAC SDU response delay.

Similarly, the majority of previous studies attempting to reduce power consumption did not pay sufficient attention to the response delay performance [4], [17], [18]. Because both T_{min} and T_{max} are the most important parameters affecting network performance metrics, they should be taken into consideration simultaneously, rather than individually. To this end, Kim *et al.* proposed an adaptive power saving mechanism (APSM) that adaptively controls sleep mode parameters by considering the inter-arrival time of the MAC SDU [19] and a schedule power saving mechanism (SPSM) for a mobile user having multiple connections [20]. However, both APSM and SPSM resulted in a longer delay time compared to the standard PSM, and thus could not be applied to high quality-of-service (QoS) connections [19], [20].

As a result, improving power savings results in a degradation of the MAC SDU response delay, which thereby indicates that the power performance should be enhanced or optimized under a specific MAC SDU response delay requirement. For this task, in our previous works [7], [8] we proposed algorithms for finding the optimal final sleep window T_{max} when the initial sleep window T_{min} is fixed. However, because both T_{min} and T_{max} are the most important parameters affecting network performances, they both should be taken into consideration; moreover, no performance evaluation models were proposed in [7], [8].

III. POWER SAVING MECHANISM IN IEEE 802.16E

Fig. 1 shows a PSC Type I, in which an MS alternates between awake and sleep modes while communicating with its serving BS. In the PSM, whenever the MS switches from awake mode to sleep mode, it sends a sleep request message (MOB_SLP-REQ) that includes sleep mode parameters such as T_{min}, T_{max}, and listening window L to its BS. Upon receiving the sleep response message (MOB_SLP-RES), the MS enters sleep mode. In sleep mode, the MS sleeps for the duration of the first sleep window T_1, which is equal to T_{min}. It then temporarily

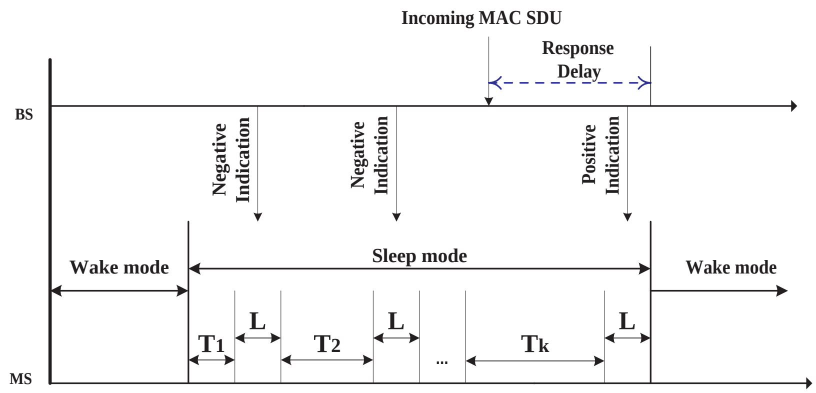

Fig. 1. Example of sleep mode operation in the IEEE 802.16e standard.

wakes up for a duration equal to the listening window L, to listen for an indication message (MOB_TRF-IND) from its BS. If this message is negative, meaning that there was no DL traffic during the previous MS sleep state, the MS will sleep again. The second sleep window T_2 is double that of T_1, and after T_2 the MS again returns to its listening state. Once the size of the sleep window reaches T_{max}, it continues this sleep window length with no further increase.

IV. ANALYTICAL MODELING

In this section, we derive the analytical models for power consumption and MAC SDU response delay in the IEEE 802.16e sleep operation. In [1], sleep window sizes are measured in units of frames and increase in a binary exponentially expanding range. For this model, let T_n denote the nth sleep window, which is given as

$$T_n = \min\{2^{n-1}T_{min}, T_{max}\},$$

where T_{min} and T_{max} are the initial and the final sleep windows, respectively. In addition, T_{min} is usually selected as a power of 2 [2], [3], [17], [18]; therefore, we have the following relationships:

$$T_{max} = 2^{M-1}T_{min} \quad \text{and} \quad T_{min} = 2^{N-1}, \tag{1}$$

where M and N are integer numbers. Then, Fig. 1 shows that the duration of the nth sleep cycle, which includes a sleep window T_n and a listening window L, is given by $C_n = T_n + L$.

The arrival of MAC SDUs at an MS is assumed to follow the Poisson distribution at a rate λ[1] (i.e., the number of MAC SDUs per time unit) [2]–[6], [17]. In this case, the MS wakes up after the nth sleep cycle if and only if no MAC SDUs arrive for the $(n-1)$ previous sleep cycles, and at least one MAC SDU comes at the nth sleep cycle. Here, let P_n denote the probability that an MS wakes up after the nth sleep cycle, P_n can then be determined such that

$$P_n = \begin{cases} 1 - e^{-\lambda C_1} & \text{for } n = 1 \\ e^{-\lambda \sum_{i=1}^{n-1} C_i} \cdot (1 - e^{-\lambda C_n}) & \text{otherwise.} \end{cases} \quad (2)$$

From (2), it can be shown that $0 < P_n < e^{-\lambda \sum_{i=1}^{n-1} C_i} < (e^{-\lambda C_1})^{n-1} < 1$ for $\lambda > 0$ and $\lim_{n\to\infty} P_n = 0$. In addition, as λ approaches 0 and ∞, P_n converges to $\lim_{\lambda\to 0} P_n = 0$, and $\lim_{\lambda\to\infty} P_1 = 1$ and $\lim_{\lambda\to\infty} P_n = 0$ for $n \neq 1$, respectively.

A. *Power consumption*

Let P be the consumed power of an MS in sleep mode; the expectation of P is then given by

$$\mathbb{E}[P] = \sum_{i=1}^{\infty} P_i \frac{\sum_{j=1}^{i} (T_j P_S + L P_L)}{\sum_{j=1}^{i} C_j} \quad (3)$$

where P_S and P_L are the power consumed in the sleep and listening windows, respectively. Note that E[P] can be re-written in terms of P_S and P_L as

$$\begin{aligned} \mathbb{E}[P] &= P_S + L(P_L - P_S) \sum_{i=1}^{\infty} P_i \frac{i}{\sum_{j=1}^{i}(T_j + L)} \\ &= P_L - (P_L - P_S) \sum_{i=1}^{\infty} P_i \frac{\sum_{j=1}^{i} T_j}{\sum_{j=1}^{i}(T_j + L)}. \end{aligned} \quad (4)$$

Then, because $P_L \geq P_S$, $\mathbb{E}[P]$ has the range $P_S \leq \mathbb{E}[P] \leq P_L$, where the lower and upper bounds correspond to cases in which the MS sleeps all the time and does not sleep at all, respectively. In (4), we see that $\mathbb{E}[P]$ is a decreasing function of T_j (i.e., T_{min} and T_{max}). Because P_n diminishes rapidly as n increases, the terms with smaller j in (4) are likely to be more dominant in determining the value of $\mathbb{E}[P]$; as a result, the effect of T_{min} on $\mathbb{E}[P]$ can be

[1] In [21], it was reported that the arrival process of the unsolicited grant service (UGS), real-time variable rate (RT-VR), and non-real-time variable rate (NRT-VR) traffic can be modeled as a Poisson process. Also, the traffic models following the Poisson distribution are suggested as traffic model for performance evaluation in [22].

considered as being more significant than T_{max}. Indeed, once T_{max} reaches a certain value, $\mathbb{E}[P]$ does not increase further and remains constant even as T_{max} continues to increase; note that the effects of T_{min} and T_{max} on $\mathbb{E}[P]$ will be further investigated in Section VI-A. In addition, as λ approaches infinity, $\mathbb{E}[P]$ converges to $\lim_{\lambda\to\infty}\mathbb{E}[P] = \frac{T_{min}P_S + LP_L}{T_{min}+L}$.

B. MAC SDU response delay

We next derive an analytical model for calculating the average time that a MAC SDU must wait for an MS to transition from sleep mode to awake mode. Let D be the MAC SDU response delay, then the expectation of D is given by [2]

$$\mathbb{E}[D] = \sum_{i=1}^{\infty} P_i \left(\frac{T_i + L}{2}\right), \tag{5}$$

which can be re-written as

$$\begin{aligned}\mathbb{E}[D] &= \frac{T_{min}+L}{2} + \frac{T_{min}}{2}\sum_{i=1}^{M-1} P_i\left(2^{i-1}-1\right) + \frac{T_{max}}{2} e^{-\lambda\left[\left(2^{M-1}-1\right)T_{min}-L+LM\right]} \\ &= \frac{T_{max}+L}{2} - \frac{1}{2}\sum_{i=1}^{M-1}\left(T_{max}-T_i\right).\end{aligned} \tag{6}$$

And from (6) it can be inferred that

$$\frac{T_{min}+L}{2} \le \mathbb{E}[D] \le \frac{T_{max}+L}{2}. \tag{7}$$

Basically, $\mathbb{E}[D]$ can be viewed as an increasing function of T_{min} and T_{max}; because P_n diminishes rapidly as n increases, the terms with smaller i in (5) are likely to be more dominant in determining the value of $\mathbb{E}[D]$. As a result, the effect of T_{min} on $\mathbb{E}[D]$ is more significant than T_{max}. In addition, as λ approaches 0 and infinity, $\mathbb{E}[D]$ converges to $\lim\limits_{\lambda\to 0}\mathbb{E}[D] = \dfrac{T_{max}+L}{2}$ and $\lim\limits_{\lambda\to\infty}\mathbb{E}[D] = \dfrac{T_{min}+L}{2}$, respectively, in accordance with the range stated in (7).

From the two analytical models above, we can see that $\mathbb{E}[P]$ is a decreasing function and $\mathbb{E}[D]$ is an increasing function of T_{min} and T_{max}. These functions indicate that reduced power consumption results in an increased MAC SDU response delay; i.e., a tradeoff relationship exists between power consumption and MAC SDU response delay. Importantly, the presence of this tradeoff implies that it is not possible to simultaneously improve both performance metrics.

V. Optimized Power-Saving Mechanism

One goal of our research is to minimize the power consumption of an MS under a given MAC SDU response delay constraint. For this task, we propose an adjustment mechanism, referred to as an optimized power-saving mechanism (OPSM), to jointly determine the optimum T_{min} and T_{max} of a PSM in the IEEE 802.16e standard. This mechanism can be regarded as a policy optimization problem [23] that minimizes the power consumption of an MS in its sleep mode, while ensuring that the MAC SDU response delay remains lower than the required bound. Due to the constraints of (1), we find N and M rather than T_{min} and T_{max}, respectively. Furthermore, as the MAC SDU arrival rate λ depends on customer behavior—which cannot be controlled—for simplicity, λ is assumed to be already known[2]. Let D_{giv} (frames) denote the MAC SDU response delay constraint. In this case, we have a set (D_{giv}, λ, L) from which the optimal N and M are to be computed for the lowest power consumption.

We formulate the power consumption minimization based on the delay constraint as follows:

$$\begin{aligned} \text{minimize}_{M,N} \quad & \mathbb{E}[P] \\ \text{subject to} \quad & \mathbb{E}[D] \le D_{giv} \\ & N, M \in \mathbb{Z}^{+}. \end{aligned} \tag{8}$$

This integer programming problem can be solved by rigorously searching a sufficiently large range for N and M. However, in order to make the search operation more tractable, we exploit the analytical models from Section IV to reduce the search spaces of both N and M. Because $T_{min} \le 2\mathbb{E}[D] - L$ in (7), we can obtain the following range for N: $1 \le N \le \lfloor \log_2 (2E[D]_{giv} - L) \rfloor + 1$, where $\lfloor x \rfloor$ is the largest integer not greater than x. This range implies that the optimal solution for N belongs to the set of $\mathcal{X} = \{1, \cdots, \lfloor \log_2 (2D_{giv} - L) \rfloor + 1\}$ for a given D_{giv}. Note, however, that no solution exists if $\lfloor 2D_{giv} - L \rfloor < 1$.

Regarding the range of M, in Fig. 1 it can be seen that the maximum MAC SDU response delay would be bounded by $D \le T_{max} + L$. As such, it is not necessary to search too large of a range of T_{max} for a given delay bound D_{giv}, as the upper bound for the range of T_{max} can be set to a value k times larger than ($D_{giv} - L$). Then, by (1), $2 \le M \le \left\lceil \log_2 \frac{k(D_{giv}-L)}{T_{min}} \right\rceil + 1$, where

[2]Due to the centralized architecture of WiMAX, it is assumed that the traffic intensity information for individual MSs is readily available.

Algorithm 1 Simple pseudo-code of the proposed OPSM

Require: D_{giv}, λ, L

Assign $N^* = \lfloor \log_2 (2E[D]_{giv} - L) \rfloor + 1$, $M^* = \left\lceil \log_2 \frac{k(D_{giv}-L)}{T_{min}} \right\rceil + 1$, $\mathbb{E}[P]^* = \infty$.
for $N = N^*$ to 1 **do**
  for $M = M^*$ to 2 **do**
    Calculate $\mathbb{E}[D]$ by (5)
    if $\mathbb{E}[D] \leq D_{giv}$ **then**
      Calculate $\mathbb{E}[P]$ by (3)
      if $\mathbb{E}[P] \leq \mathbb{E}[P]^*$ **then**
        $\mathbb{E}[P]^* = \mathbb{E}[P]$,$N^* = N$,$M^* = M$
      end if
    end if
  end for
  $T_{min} = 2^{N^*-1}$, $T_{max} = 2^{M^*-1} T_{min}$
end for

$\lceil x \rceil$ is the smallest integer not less than x; in our mechanism, k is usually set at 10. Hence, the search space for M can be given by the set $\mathcal{Y} = \{2, \cdots, \left\lceil \log_2 \frac{k(D_{giv}-L)}{T_{min}} \right\rceil + 1\}$.

To solve the optimization problem in (8), we search the spaces $\mathcal{X}$ and $\mathcal{Y}$ for N and M, respectively, as shown in Algorithm 1. Based on this condition, these search spaces are considerably more limited than the original spaces for both N and M in (8). This simplified version of Algorithm 1 can then be further optimized by exiting the loops, based on the finding that $\mathbb{E}[P]$ is inversely proportional to N and M. Note that these optimal solutions can be computed in advance and be tabulated for various values of D_{giv}, λ, and L.

VI. Simulation Results

A. Numerical modeling validation

First, we validate our proposed analytical models using MATLAB simulations, based on the following parameters: L = 1 (frame); P_S = 1; and P_L = 30. The simulations time is 1,000,000 CPU seconds. The given MAC SDU response delay constraint (D_{giv}) is set to 5. Fig. 2 shows

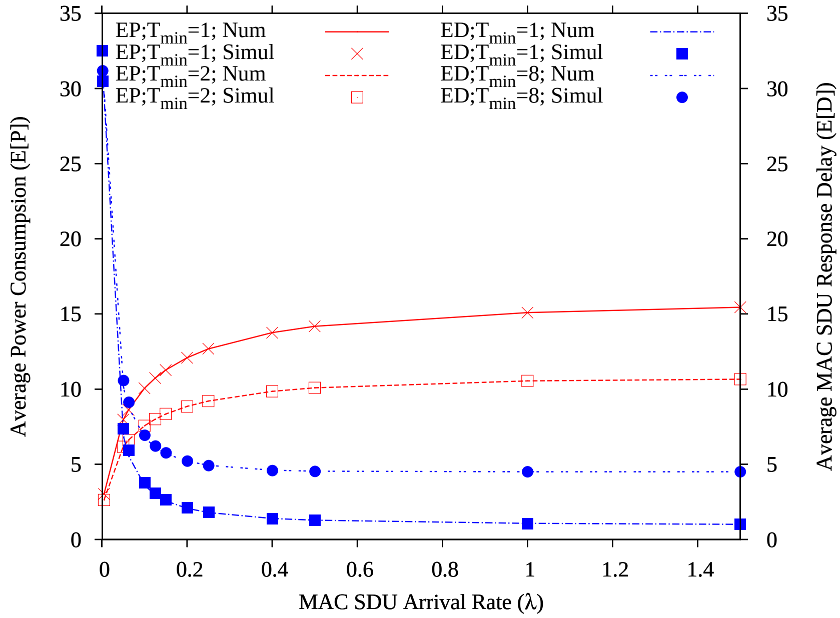

Fig. 2. Model validation for power consumption and MAC SDU response delay with respect to the MAC SDU arrival rate λ.

the average power consumption per time unit and MAC SDU response delay for an MS in sleep mode with respect to λ for different T_{min} when T_{max} = 512. In the figure, we observe that $\mathbb{E}[P]$ increases rapidly and levels off as λ increases, and that the MS sleeps more when λ is low. However, as λ increases, the MS transitions from sleep to listening states more often, and because the power consumed in a listening state is much higher than in a sleep state, a higher λ results in a higher $\mathbb{E}[P]$. As explained in Section IV-A, as λ tends to infinity, $\mathbb{E}[P]$ approaches $\frac{T_{min}E_s+LE_L}{T_{min}+L}$. The figure also shows the average MAC SDU response delay with respect to λ, where it can be seen that $\mathbb{E}[D]$ decreases exponentially and levels off as λ increases. In accordance with the analyses in Section IV-B, $\mathbb{E}[D]$ changes from $\frac{T_{max}+L}{2}$ to $\frac{T_{min}+L}{2}$ as λ increases. As such, the analytical results for all cases are seen to be very close to the simulation results, thus confirming that our proposed analytical models are correct. The figure also confirms that the power consumption and MAC SDU response delay have a tradeoff relationship.

Fig. 3 presents the effects of T_{min} on $\mathbb{E}[P]$ and $\mathbb{E}[D]$ for different λ when M = 4. In the figure, $\mathbb{E}[P]$ exponentially decreases with respect to T_{min} due to the fact that the higher the T_{min}, the longer the MS is in sleep mode. In addition, $\mathbb{E}[D]$ is linearly proportional to T_{min}, especially when λ is large. Also, note that $\mathbb{E}[D]$ converges to $\frac{T_{min}+L}{2}$ as λ approaches infinity.

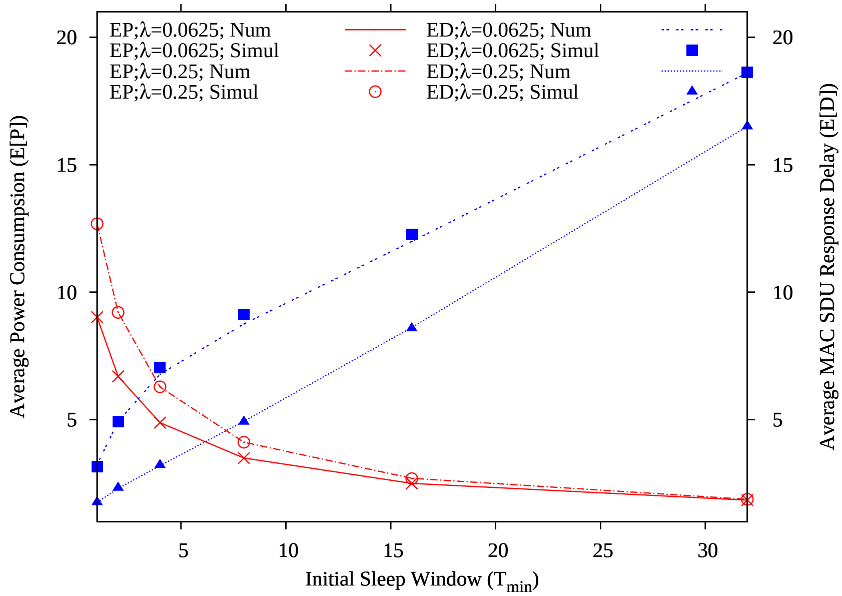

Fig. 3. Model validation for power consumption and MAC SDU response delay with respect to the initial sleep window T_{min}.

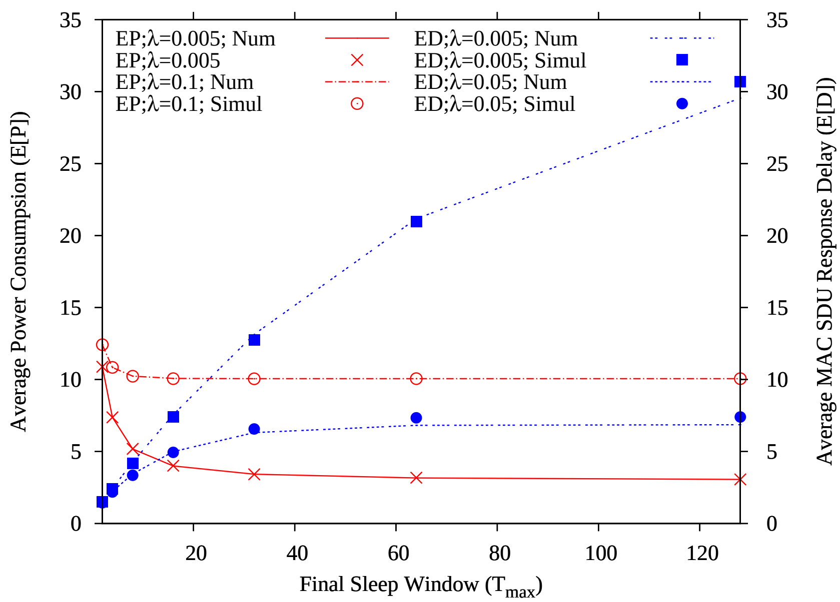

Fig. 4. Model validation for power consumption and MAC SDU response delay with respect to the initial sleep window T_{max}.

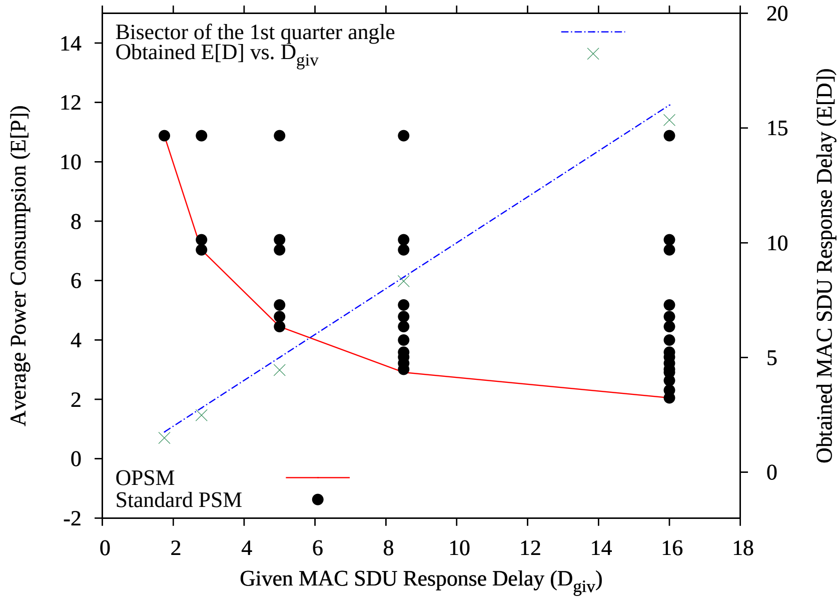

Fig. 5. Performance evaluation for power consumption and MAC SDU response delay with respect to D_{giv} when λ = 0.05.

Fig. 4 presents the effects of T_{max} on $\mathbb{E}[P]$ and $\mathbb{E}[D]$ for different λ when T_{min} = 1. When T_{max} is small, $\mathbb{E}[P]$ rapidly decreases, and as T_{max} increases, it levels off. The saturated value of $\mathbb{E}[P]$ depends on λ, i.e., a smaller λ gives a lower saturated $\mathbb{E}[P]$; similarly, $\mathbb{E}[D]$ gradually increases and levels off at a certain value of T_{max}. These results imply that the effect of T_{max} on the performance is not significant when T_{max} is large, because with a sufficiently large M the probability that an MS wakes up after M sleep cycles is almost zero, due to $\lim_{n\to\infty} P_n = 0$.

B. OPSM performance evaluation

We then investigated the amount of power consumption reduced by the proposed OPSM, while also ensuring that the MAC SDU delay constraint is satisfied. Fig. 5 presents a performance comparison between the OPSM and all the cases of the standard PSM with respect to the MAC SDU response delay constraint when the MAC SDU arrival rate is fixed at 0.05. The black dots in the figure represent the power consumption for the original PSM, in which the MAC SDU delay is equal to or lower than each delay constraint D_{giv} on the x-axis. The figure shows that in all cases the OPSM successfully selects the N and M pair that consumes the least power. For the standard PSM, if the T_{min} and T_{max} pair is not properly chosen, the power consumption could be significantly larger than the optimal value, especially when D_{giv} is large. In a worst case scenario, an inappropriate OPSM can potentially reduce the power consumption by up to 70%. As a result, however, an appropriately selected OPSM can significantly improve the lifetime performance of MSs in IEEE 802.16e systems. The figure also confirms that the MAC SDU delay obtained by OPSM satisfies the delay constraint, thereby also confirming that the OPSM not only minimizes the power consumption but also guarantees the MAC SDU response delay.

VII. Conclusion

In this paper, we proposed analytical models for two of the most important network performance metrics in IEEE 802.16e systems: the average power consumption and the average MAC SDU response delay of an MS in its sleep mode. We then showed that a tradeoff relationship exists between the two performance metrics; i.e., as the power consumption is improved, the MAC SDU response delay becomes degraded, and vice versa. Next, we proposed an optimized power-saving mechanism (OPSM), which jointly determined a suitable T_{min} and T_{max} pair in order to minimize the power consumption under a given MAC SDU response delay constraint. As a result, through both numerical analyses and subsequent simulations, we showed that the T_{min} and T_{max} pair obtained by the OPSM indeed minimizes the power consumption of MSs in sleep mode, and thus effectively extends their lifetimes while guaranteeing MAC SDU response delays.

VIII. Acknowledgments

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