Delay-guaranteed Energy Saving Algorithm for the Delay-sensitive Applications in IEEE 802.16e Systems

Dinh Thi Thuy Nga, Min-Gon KIM, *Student Member,* IEEE, and Minho Kang, *Senior Member*, IEEE

Abstract —*The 802.16e power management helps to increase the lifetime of Mobile Subscriber Stations (MSSs) by reducing their energy consumption, but this reduction results in Medium Access Control (MAC) Service Data Unit (SDU) response delay. Hence, both energy consumption and MAC SDU response delay are important performance metrics; however, they have a trade-off relationship. To guarantee the delay constraints of delay-sensitive applications, operating parameters in sleep-mode operation such as minimum sleep interval, T_{min}, and maximum sleep interval, T_{max}, should be considered seriously. Especially, large T_{max} results in high MAC SDU response delay. However, in the IEEE 802.16e standard, this point is not given enough attention. In this paper, we first propose a numerical model to determine T_{max} based on MAC SDU response delay. Then, we propose a Delay -Guaranteed Energy Saving (DGES) algorithm to minimize energy consumption with a given MAC SDU response delay by finding the optimal T_{max} under a fixed T_{min}. Our proposed numerical model and DGES algorithm are verified by simulation results*[1].

Index Terms — IEEE 802.16e, energy consumption, sleep – mode operation, MAC SDU response delay.

I. INTRODUCTION

The explosive growth of the Internet over recent decades has led to a substantial increase in demand for high speed and ubiquitous Internet access. Broadband Wireless Access (BWA) has the potential to address these demands. IEEE 802.16e (Mobile World Interoperability for Microwave Access - Mobile WiMAX) is a standard which aims to provide low cost, high data rate, and mobility to residential and small business applications [1]-[3]. It is expected to fill the gap between high data rate wireless Local Area Networks and mobile cellular systems [1]. In order to continuously provide convergence and seamless services to users, we have to explore energy management of Mobile Subscriber Stations (MSSs) in IEEE 802.16e systems.

To efficiently manage energy in IEEE 802.16e systems, an MSS alternates between wake-mode and sleep-mode respectively whenever it is or is not communicating with its Base Station (BS) and vice-versa. Sleep-mode operation is generally controlled by minimum sleep interval, T_{min}, and maximum sleep interval, T_{max}. Performance metrics including energy consumption and Medium Access Control (MAC) Service Data Unit (SDU) response delay are affected by these parameters. In addition, there is a trade-off relationship between energy consumption and MAC SDU response delay [6]. Thus, to reach a comprehensive understanding of these problems, it is essential to examine effects of T_{min} and T_{max} on performance metrics and to determine suitable sizes for them based on the requirements of applications.

There have been several studies focusing on sleep-mode operation. Yang Xiao analytically modeled the sleep-mode operation in IEEE 802.16e and evaluated the effects of T_{min}, T_{max} and MAC SDU arrival rate on networks performance metrics [4]. Yan Zhang proposed an analytical model to evaluate energy management in IEEE 802.16e Wireless MAN [5]. In [6], Jun-Bae Seo investigated the queuing behavior of sleep-mode in terms of dropping probability and in terms of mean waiting time of packets in the queue of BS. In [7], the authors used a semi-Markov chain to derive packet delay and average energy consumption of sleeping, listening, and waking-up states. Junfeng XIAO changed minimum sleep interval at low MAC SDU arrival rate to reduce energy consumption [8].

Although reducing energy consumption is important, the MAC SDU response delay also has to be seriously considered because some applications are very sensitive to latency or jitter. For example, in IEEE 802.16m, maximum state transition latency in Physical and MAC layers is recommended to be 100ms or less [9] while latency for voice and video conferencing services should not exceed 150ms [10]. Also, jitter for interactive-video should be no more than 30ms [11]. Hence, to address the requirements of some delay-sensitive applications, it is essential to guarantee MAC SDU response delay. To the best of our knowledge; however, most studies have focused only on energy consumption [4] - [8]. Although the trade-off relationship between energy consumption and MAC SDU response delay is mentioned in [6], no researcher has dealt with energy consumption while taking MAC SDU response delay into consideration. Hence, in this paper, we consider how to minimize energy consumption with a given MAC SDU response delay and with T_{min} has been determined. Specifically, we propose a numerical model to determine T_{max} with a given MAC SDU response delay constraint. Based on this numerical model, we propose a Delay-Guaranteed Energy Saving (DGES)

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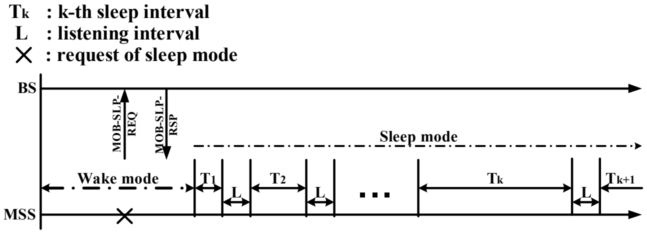
algorithm which guarantees the required latency and jitter by obtaining an optimal T_{max} for a fixed T_{min}. We also validate our numerical model and DGES algorithm by simulation evaluations. The proposed numerical model and DGES algorithm can help to achieve an efficient way of reaching target performance in delay-sensitive applications.

The rest of this paper is organized as follows. Section II introduces the sleep-mode operation in IEEE 802.16e. Section III presents a numerical model to calculate T_{max} under MAC SDU response delay constraint. In Section IV, our proposed DGES algorithm for obtaining an optimal T_{max} is described. Performance evaluation is shown in Section V. Finally, Section VI concludes this paper.

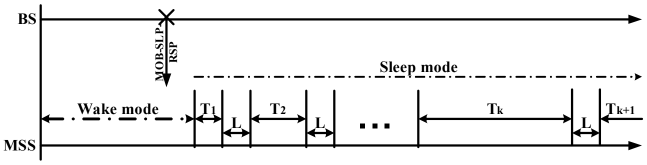
II. THE SLEEP MODE OPERATION IN IEEE 802.16E

This Section explains sleep-mode operation in IEEE 802.16e MAC and presents key ideas for performance enhancement. In order to reduce energy consumption, an MSS alternates between wake-mode and sleep-mode during operation as it communicates with its BS. Before an MSS goes into sleep-mode, parameters for sleep-mode operation such as T_{min}, T_{max}, and listening interval, L, have to be set either by MSS or by its BS. With sleep response message (MOB-SLP-RSP) from the BS, the MSS enters sleep-mode. If the BS wants the MSS to transit to wake-mode, it sends a positive indication message (MOB-TRF-IND) to the MSS during listening state. Then the MSS transits back to wake-mode after receiving a positive MOB-TRF-IND message.

Fig. 1 shows two cases of initiating sleep-mode patterns, categorized by which station wants to make an MSS transit to sleep-mode. First, when an MSS itself wants to be in sleep-mode, it sends a sleep request message (MOB-SLP-REQ) which includes T_{min}, T_{max}, and L to its BS as shown in Fig. 1(a). After the BS receives the MOB-SLP-RSP message, it sends a MOB-SLP-RSP message to the MSS. Upon receiving the MOB-SLP-RSP message, the MSS enters sleep-mode. Secondly, sleep-mode can also be initiated by a BS as shown in Fig. 1 (b). When a BS wants the MSS to be in sleep-mode, it sends a MOB-SLP-RSP message to the MSS. After the MSS receives the MOB-SLP-RSP message, it enters sleep-mode. The MOB-SLP-RSP message is sent from the BS to MSSs on a Broadcast CID or on the MSS's basic CID in response to a MOB-SLP-REQ message, or it may be sent unsolicited.

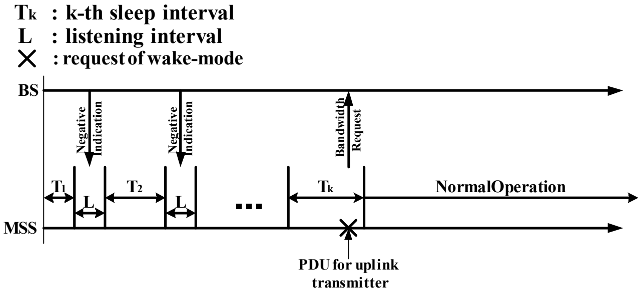


(a) MSS initiating sleep mode

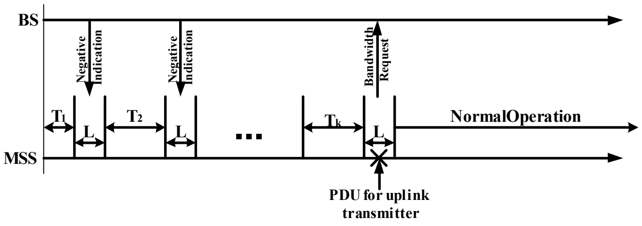


(b) BS initiating sleep mode

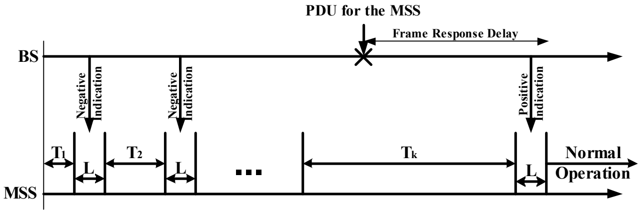
Fig. 1. Initiating sleep-mode.



(a) MSS initiating awakening - 1



(b) MSS initiating awakening - 2



(c) BS initiating awakening

Fig. 2. Initiating awakening.

Fig. 2 illustrates initiating a transition to wake-mode. Either MSSs or BSs can initiate this transition. Sleep-mode consists of sleep cycles, each cycle consists of a sleep interval and a listening interval. After the first sleep interval T_1, which equals T_{min}, the MSS transits to listening state for a duration of L; then, it listens for a MOB-TRF-IND message broadcasted by the BS. The MOB- TRF-IND message indicates whether there was traffic addressed to the MSS during its sleep-mode. If the MOB-TRF-IND message indication is negative, meaning there was no traffic, the MSS continues to be in sleep-mode. In this case, the current sleep interval would double the previous sleep interval if the previous sleep interval is less than T_{max}. In case the previous sleep interval is T_{max}, the current sleep interval remains T_{max} unless the MSS goes into wake-mode. Let T_k be the k-th sleep interval, then T_k is determined by

$$T_k = \begin{cases} 2T_{k-1} & if\ T_{k-1} < T_{max} \\ T_{max} & otherwise \end{cases}. \tag{1}$$

When the MSS has some Protocol Data Units (PDUs) to transmit to its BS, it can transit to wake-mode by sending a bandwidth request message to the BS when it is in sleeping state as shown in Fig. 2(a) or is in listening state as shown in Fig. 2(b). When the MSS initiates transition to wake-mode, there is no MAC SDU response delay regardless of the sleep interval. Therefore, longer sleep intervals, i.e. larger values for T_{min} and T_{max} have better effects on energy consumption. However, in case the BS initiates wake-mode transition as shown in Fig. 2 (c), additional MAC SDU response delay would occur since the BS should wait until the listening state of MSSs. Thus, attention needs to be paid to energy consumption and to the reduction of the MAC SDU response delay. Energy consumed in sleeping state is much smaller than that in listening state; therefore, from the energy saving viewpoint, longer sleep intervals produce better power management performance but they cause more MAC SDU response delay. In order to achieve targeted performance, we need to carefully consider the characteristics of the two initiating awakening and the effects of sleep intervals. In light of this, the following Sections will show numerical model and operating procedure for our proposed algorithm.

III. NUMERICAL MODEL

This Section presents numerical model showing the relationship between maximum sleep interval and MAC SDU response delay. In fact, MAC SDU response delay as well as energy consumption depends on minimum sleep interval, T_{min}, maximum sleep interval, T_{max}, and MAC SDU arrival rate, λ, or MAC SDU interarrival time, $T_I = 1/\lambda$ [4]-[8], [12]. However, λ or T_I depends on customer behaviors; therefore, we cannot do anything about λ or T_I.

With a given MAC SDU response delay, it is difficult to find both optimal T_{min} and optimal T_{max} simultaneously. In addition, it can be inferred from [12] that T_{min} is sensitive to energy consumption, and T_{max} is sensitive to MAC SDU response delay. Therefore, we assume that T_{min} has been determined, and based on T_{min} we can obtain the optimal T_{max} for energy consumption. Furthermore, this assumption helps us examine the effects of T_{max} on MAC SDU response delay more clearly.

Let M be an integer such that

$$2^{M-1}T_{min} = T_{max}. \tag{2}$$

From (1), T_k is calculated as follows

$$T_k = \begin{cases} 2^{k-1}T_{min} & with\ k < M \\ T_{max} & otherwise \end{cases}. \tag{3}$$

Let n be the number of sleep intervals before an MSS goes into wake-mode. In addition, let the arrival rate of MAC SDUs to an MSS follows Poisson distribution with a rate λ, meaning that the mean interarrival time is $T_I = 1/\lambda$. Consider sleep cycle k, which includes a sleep interval T_k and a listening interval L. Assume that L is fixed. The duration of sleep cycle k is $(T_k + L)$. Let P_i be the probability that there are i MAC SDUs arriving during $(T_k + L)$. Then, the probability that there is at least one MAC SDU arrival during $(T_k + L)$ is

$$P_1 + P_2 + ... + P_n + ... = \sum_{k=1}^{\infty} P_k = 1 - P_0. \tag{4}$$

Since arrival rate follows Poisson distribution, the probability that there is no MAC SDU arrival during the k-th sleep cycle is

$$P_0 = \frac{\left(\lambda\left(T_i + L\right)\right)^0}{0!} e^{-\lambda(T_i+L)} = e^{-\lambda(T_i+L)}. \tag{5}$$

Therefore,

$$P_1 + P_2 + ... + P_n + ... = 1 - P_0 = 1 - e^{-\lambda(T_i+L)}. \tag{6}$$

The MSS transits to wake-mode from sleep-mode at the end of the k- th sleep cycle if and only if there is at least one MAC SDU addressed to the MSS during $(T_k + L)$ and no MAC SDU addressed to that MSS in previous cycles. Then

$$\begin{aligned} P(n=k) &= P\begin{pmatrix} no\,MAC\ \ SDU\ in\ \ sleep\ \ cycle\ 1,2,..k-1; \\ MAC\ \ SDUs\ \ exits\,in\ \ k-th\ \ sleep\ \ cycle \end{pmatrix} \\ &= P\left(no\,MAC\ \ SDU\ in\ \ sleep\ \ cycle\ 1,2,..k-1\right) \\ &\cdot P\left(MAC\ \ SDUs\ \ exits\,in\ \ k-th\ \ sleep\ \ cycle\right) \\ &= e^{-\lambda\sum_{i=1}^{k-1}(T_i+L)}\left(1-e^{-\lambda(T_k+L)}\right) \\ &= e^{-\frac{1}{T_I}\sum_{i=1}^{k-1}(T_i+L)}\left(1-e^{-\frac{1}{T_I}(T_k+L)}\right). \end{aligned} \tag{7}$$

MAC SDU response delay performance metric is represented by average MAC SDU response delay [4]. Let R be the MAC SDU response delay, expectation of R is [4]

$$E\left[R\right] = \sum_{k=1}^{\infty} P\left(n=k\right)\frac{T_k + L}{2}. \tag{8}$$

Since $T_k \geq T_{min}$ with every integer $k \geq 1$, we have

$$E\left[R\right] \geq \frac{T_{min} + L}{2}. \tag{9}$$

The equality occurs when $T_k = T_{min}$, meaning that T_{min} equals T_{max}. Therefore, the lower bound of $E\left[R\right]$ is

$$E\left[R\right]_{min} = \frac{T_{min} + L}{2}. \tag{10}$$

In addition, since $T_{max} \geq T_k$ with every integer $k \geq 1$, we have

$$E\left[R\right] \leq \frac{T_{max} + L}{2}. \tag{11}$$

or

$$T_{max} \geq 2E\left[R\right] - L. \tag{12}$$

It can be inferred from (2) and (12) that

$$2^{M-1}T_{min} \geq 2E\left[R\right] - L. \tag{13}$$

or

$$M \geq \log_2\left(\frac{2E\left[R\right] - L}{T_{min}}\right) + 1. \tag{14}$$

Let $\lceil A \rceil$ be the smallest integer which is equal to or greater than A. Since M is an integer, we have

$$M \geq \left\lceil \log_2 \left(\frac{2E[R]-L}{T_{min}} \right) + 1 \right\rceil. \tag{15}$$

Rewrite (8) as

$$\begin{aligned} E[\mathrm{R}] &= \frac{L}{2} \sum_{k=1}^{\infty} \Pr(n=k) + \sum_{k=1}^{M-1} \Pr(n=k) \frac{T_k}{2} + \frac{T_{max}}{2} \sum_{k=M}^{\infty} \Pr(n=k) \\ &= \frac{L}{2} + \sum_{k=1}^{M-1} \Pr(n=k) \frac{T_j}{2} + \frac{T_{max}}{2} \sum_{k=M}^{\infty} \Pr(n=k) \\ &= \frac{L}{2} + S_1 + S_2. \end{aligned} \tag{16}$$

where $S_1 = \sum_{k=1}^{M-1} \Pr(n=k) \frac{T_j}{2}$ and $S_2 = \frac{T_{max}}{2} \sum_{k=M}^{\infty} \Pr(n=k)$.

It can also be inferred from (7) that $P(n=k) > 0$ for every integer k; therefore, $E[R]$ is an increasing function of T_{max}. However, when T_{max} is sufficiently large, $P(n=k)$ calculated by (7) is extremely small. Hence, $E[R]$ stays constant even when T_{max} increases. This remark will be confirmed by simulations in Section V. The value of $E[R]$ which does not change when T_{max} continues increasing is the upper bound of average MAC SDU response delay, called $E[R]_{max}$.

Rewrite $P(n=k)$ from (7) as

$$P(n=k) = \begin{cases} e^{\frac{1}{T_I}(T_{min}+L)} e^{-\frac{1}{T_I}\left(2^{k-1} T_{min} + kL\right)} \left(1 - e^{-\frac{1}{T_I}\left(2^{k-1} T_{min} + L\right)} \right); & k < M \\ e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]} & ; k \geq M \end{cases}. \tag{17}$$

Then

$$\begin{aligned} S_1 &= \sum_{k=1}^{M-1} \Pr(n=k) \frac{T_k}{2} \\ &= T_{min} e^{\frac{1}{T_I}(T_{min}+L)} \sum_{k=1}^{M-1} 2^{k-2} e^{-\frac{1}{T_I}\left(2^{k-1} T_{min} + kL\right)} \left(1 - e^{-\frac{1}{T_I}\left(2^{k-1} T_{min} + L\right)} \right). \end{aligned} \tag{18}$$

and

$$S_2 = \frac{T_{max}}{2} \sum_{k=M}^{\infty} P(n=k) = \frac{T_{max}}{2} e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]}. \tag{19}$$

Replace (18) and (19) into (16)

$$E[R] = \frac{L}{2} + S_1 + \frac{T_{max}}{2} e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]}. \tag{20}$$

Assume that we have found T_{max} which minimizes energy consumption for a given average MAC SDU response delay. Then, T_{max} must satisfy the following inequality

$$\frac{L}{2} + S_1 + \frac{T_{max}}{2} e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]} \leq E[R]. \tag{21}$$

or

$$T_{max} \leq \frac{2E[R] - 2S_1 - L}{e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]}}. \tag{22}$$

In [4], when T_{max} increases, the energy consumption of MSSs in sleep-mode operation decreases but $E[R]$ increases. Therefore, energy consumption and average MAC SDU response delay have a trade-off relationship; hence, we cannot improve both simultaneously. This is also confirmed in [6]. Therefore, in order to minimize energy consumption with a given $E[R]$, we should find the maximum T_{max}. From (22), the optimal T_{max} is given by

$$T_{max_{optimal}} = \frac{2E[R] - 2S_1 - L}{e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]}}. \tag{23}$$

Equation (23) shows how T_{max} depends on $E[R]$. As mentioned above, with T_{min} having been determined, there exist lower and upper bounds of $E[R]$, called $E[R]_{min}$ and $E[R]_{max}$ respectively. If the required $E[R]$, called $E[R]_{req}$, is lower than $E[R]_{min}$, there is no satisfactory T_{max} since $E[R]_{req}$'s being lower than $E[R]_{min}$ makes the right hand side of (22) lower than zero. In addition, if $E[R]_{req}$ is equal or higher than $E[R]_{max}$, any $T_{max} = 2^{k-1} T_{min}$ for every integer $k \geq 1$ is the solution. When $E[R]_{min} \leq E[R]_{req} < E[R]_{max}$, $E[R]_{req}$ is a strictly increasing function of T_{max}; therefore, there is a unique optimal T_{max} corresponding to each $E[R]_{req}$. With these values of $E[R]_{req}$, the optimal T_{max} calculated by (23) minimizes energy consumption in sleep-mode operation of an MSS because if we increase T_{max} to further reduce energy consumption, MAC SDU response delay will exceed its limit. Hence, (23) gives us the formula to calculate optimal T_{max} in terms of energy consumption with a given $E[R]$. In addition, T_{max} is determined if ($E[R]$, T_I, T_{min}, M, L) are known. However, since M depends on T_{min} and T_{max} by (2), and L is usually fixed, from ($E[R]$, T_I, T_{min}, L) we can find optimal T_{max}. Next Section describes our proposed algorithm to find optimal T_{max} based on ($E[R]$, T_{min}, T_I, L) sets.

IV. DELAY- GUARANTEED ENERGY SAVING ALGORITHM

This Section presents a simple but effective algorithm, called Delay-Guaranteed Energy Saving (DGES) algorithm, to find optimal T_{max} which minimizes energy consumption with a given average MAC SDU response delay.

Assume that T_{min} has been determined and that L is fixed. Since T_I depends on customers' behaviors as mentioned in Section III, T_I is also supposed to be known. The optimal T_{max}

is calculated either by (2) or by (23). Furthermore, (15) gives us lower bound of M. Combining these constraints, T_{max} can be found based on ($E[R]$, T_{min}, T_I, L) sets.

From Section III, we see that with T_{min} having been determined, there exist lower and upper bounds of $E[R]$, called $E[R]_{min}$ and $E[R]_{max}$ respectively. Therefore, if $E[R]_{req}$ is lower than $E[R]_{min}$, T_{max} does not exit. On the other hand, if $E[R]_{req}$ is equal or greater than $E[R]_{max}$, any solution of optimal T_{max} has the form $T_{max} = 2^{k-1}T_{min}$ for every integer $k \geq 1$. In case $E[R]_{req}$ lies in $\left[E[R]_{min}, E[R]_{max}\right)$, there is a unique optimal T_{max}. Since there are two ways to calculate the optimal T_{max} by (2) and by (23), we calculate optimal T_{max} by these two ways, obtaining T_{max1} and T_{max2} respectively. Then, we compare T_{max1} and T_{max2}. If the optimal T_{max} exits, the two results must be the same. However, there is always a small difference between them caused by programming; therefore, we say $T_{max1} = T_{max2}$ if their relative difference calculated by $|T_{max1} - T_{max2}| / T_{max1}$ is less than 0.1%. Based on these expatiations, our proposed DGES algorithm consists of the following steps:

```
Step 1: Calculate $E[R]_{min} = \frac{T_{min} + L}{2}$.

Step 2: Calculate $E[R]_{max}$ by increasing $M$ in (16) until $E[R]$ stops increasing.

Step 3: If ( $E[R]_{req} \geq E[R]_{max}$ )
            $T_{max} = 2^{k-1}T_{min}$, $k \geq 1$.
        Else
            If ( $E[R]_{req} < E[R]_{min}$ )
                $T_{max}$ does not exit.
            Else
                Go to Step 4.

Step 4: Calculate $M = \left\lceil \log_2\left(\frac{2E[R]-L}{T_{min}}\right) + 1 \right\rceil$.

Step 5: Calculate $T_{max1} = 2^{M-1}T_{min}$.

Step 6: Calculate $T_{max2}$ by (23)
            $T_{max2} = \frac{2E[R] - 2S_1 - L}{e^{-\frac{1}{T_I}\left[\left(2^{M-1}-1\right)T_{min} - L + LM\right]}}$.

Step 7: Compare $T_{max1}$ and $T_{max2}$.
        If ($|T_{max1} - T_{max2}| / T_{max1} < 0.001$)
            Go to Step 9.
        Else
            Go to Step 8.

Step 8: $M = M + 1$ and go back to Step 5.

Step 9: Calculate $T_{max} = 2^{M-1}T_{min}$.
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The above steps are further illustrated in Fig. 3.

When $E[R]_{req}$ is within $\left[E[R]_{min}, E[R]_{max}\right)$, the optimal T_{max} exist uniquely. Therefore, our proposed DGES algorithm always converges. Since the average MAC SDU response delay will become saturated quickly after several values of M, we only need to iterate the above procedure several times. Hence, our proposed DGES algorithm is simple.

V. PERFORMANCE EVALUATION

In this Section, we first compare the results of our proposed numerical model with simulation results. Then, we demonstrate how our proposed DGES algorithm achieves the optimal maximum sleep interval. Finally, we compare energy consumption with a given MAC SDU response delay of MSS in sleep-mode obtained by our proposed DGES algorithm with all possible energy consumptions obtained by original IEEE 802.16e standard.

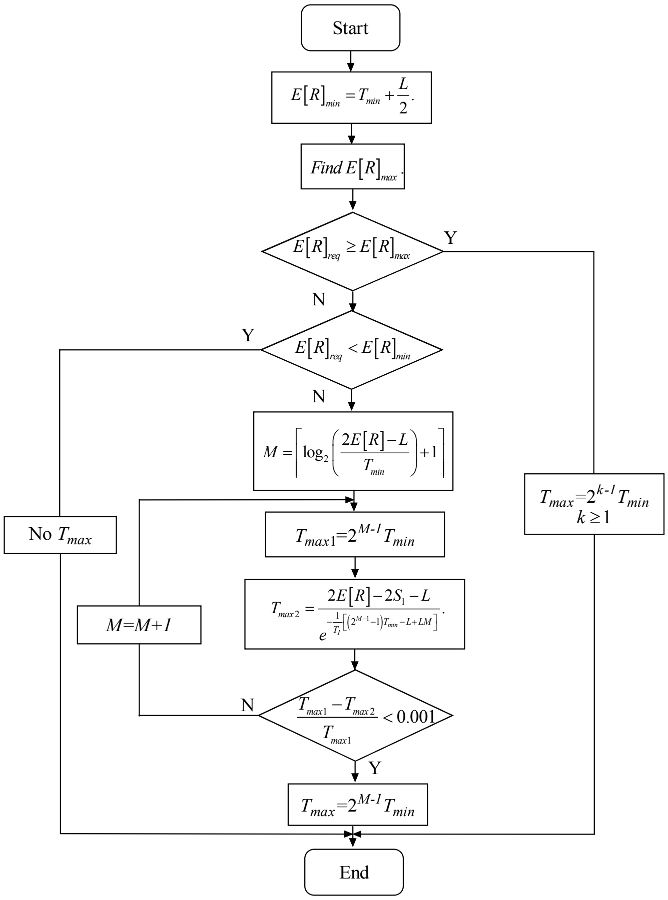

Fig. 3. Flow chart of DGES algorithm.

Let E_S and E_L be energy consumption per unit time in the sleep interval and in listening interval respectively. In our simulation, we set L=1, E_S=1 and E_L=10. The simulation time is 1,000,000 CPU sec.

Fig. 4, Fig. 5 and Fig. 6 compare the results of our proposed numerical model, formula (20), with simulation results. Fig. 4 shows the relationship between T_{max} and $E[R]$ when T_{min} equals 1 under different T_I's. The relationship can be divided into two phases. First, $E[R]$ is proportional to T_{max}. This is because after several first sleep intervals, the sleep interval becomes T_{max}. Hence, when T_{max} increases, the duration for a sleep cycle including a sleep interval and a listening interval will be increased, making MAC SDUs arriving in sleep duration wait for a longer time. This makes $E[R]$ increase. In the second phase; however, when T_{max} reaches a certain value, $E[R]$ stops increasing. The reason is that when T_{max} is large enough, it takes a number of sleep cycles for the sleep interval to equal T_{max}. Because the traffic addressed to an MSS follows Poisson distribution, calculation by (7) and simulation show us that the probability that MAC SDUs arrive at the sleep cycle in which the sleep interval equals T_{max} and no MAC SDUs have arrived in previous sleep cycles is almost zero. In other words, there are no MAC SDUs arriving in that cycle. Hence, $E[R]$ stays constant. This phase is illustrated by the straight line in Fig. 4. Furthermore, the smaller the value of T_I is, the quickly saturate phenomenon occurs because the phenomenon that T_{max} will have no effects on average MAC SDU response delay occurs earlier. In cases T_I equals 32 and 64, the saturation will occur with larger values of T_{max}. In addition, with a given T_{min}, we only consider the value of $E[R]$ that gives a unique T_{max}. That is the $E[R]$ lying in $\left[E[R]_{min}, E[R]_{max}\right)$. As explained above in Section III, there is no suitable T_{max} if $E[R]$ is less than $E[R]_{min}$ and many T_{max} if $E[R]$ is equal or greater than $E[R]_{max}$. In addition, when the arrival rate λ of MAC SDUs increases, or T_I decreases, $E[R]$ decreases. This is because increasing λ makes more MAC SDUs wait at the same time. As a result, the average time for each MAC SDU will be smaller. Similarly, Fig. 5 and Fig. 6 show the same relationship between T_{max} and $E[R]$ when T_{min} equals to 2 and 4 respectively. As illustrated in the Figures, the simulation results match numerical results pretty well.

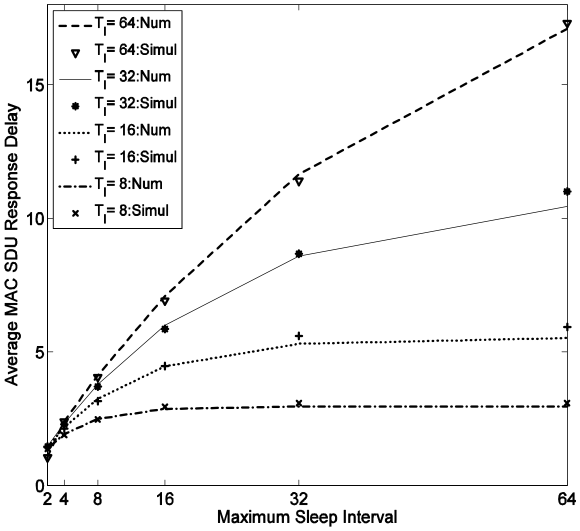

Fig. 4. ***T_{max}* and *E[R]* when *T_{min}* is 1.**

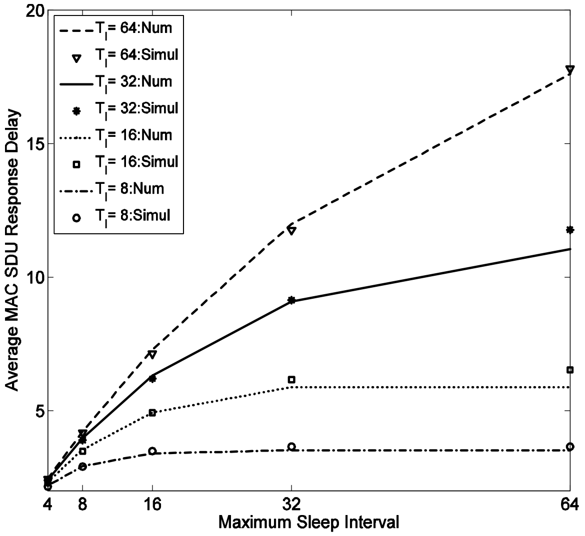

Fig. 5. ***T_{max}* and *E[R]* when *T_{min}* is 2.**

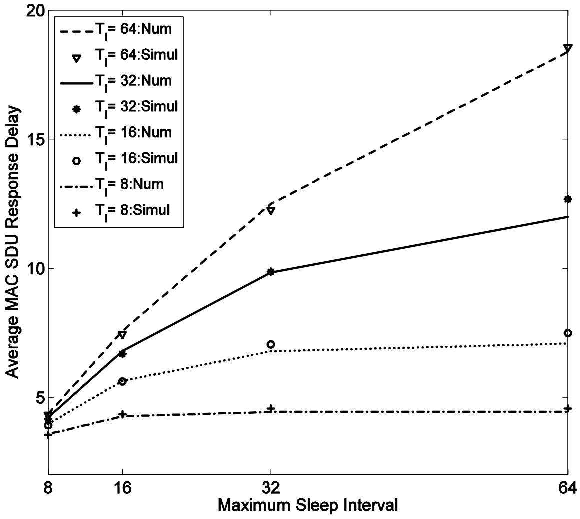

Fig. 6. ***T_{max}* and *E[R]* when *T_{min}* is 4.**

Fig. 7 describes how our proposed DGES algorithm achieves the optimal T_{max} from the required MAC SDU response delay when T_{min} is 1. We also compare the results obtained by the DGES algorithm with simulation results. Once again, as explained in Section III, if $E[R]_{req} < E[R]$, no T_{max} satisfies MAC SDUs response delay condition. When $E[R]$ is within $E[R]_{min}$ and $E[R]_{max}$, there is unique optimal T_{max}. If $E[R]_{req} \geq E[R]_{max}$, any T_{max} has form $T_{max} = 2^{k-1}T_{min}$ where $k \geq 1$ is optimal solution. Similarly, Fig. 8 and Fig. 9 show the same relationship when T_{min} is 2 and 4 respectively. Also, as illustrated in the Figures, the numerical results match pretty well with simulation results.

Next, we will show how energy consumption is improved by our proposed DGES algorithm. Energy consumption is defined as the energy consumed by an MSS in sleep-mode operation during simulation time. With a given average MAC SDUs response delay, there may exist several suitable T_{max}'s which makes average MAC SDU response delay equal to or less than the required one. These T_{max}'s result in corresponding energy consumptions. The DGES algorithm finds the maximum of these possible T_{max} which minimizes energy consumption since when T_{max} increases, energy consumption decreases [4]. We compare the energy consumption obtained by our DGES algorithm with all possibilities of energy consumption obtained by the original IEEE 802.16e standard. Fig. 10 compares the energy consumption obtained by our DGES algorithm with all possible energy consumptions obtained by the original IEEE 802.16e standard when T_{min} is 1 and T_I is 8. Among all possible values of T_{max} and the corresponding energy consumptions, our proposed algorithm gives the minimum energy consumption. The difference among energy consumptions is large, especially

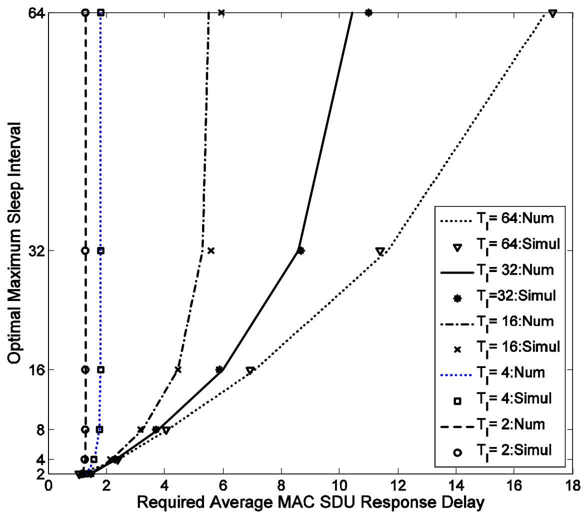

Fig. 7. T_{max} and $E[R]$ when T_{min} is 1.

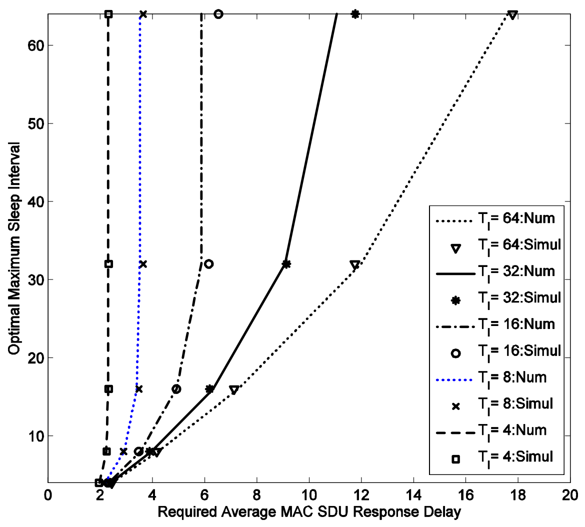

Fig. 8. T_{max} and $E[R]$ when T_{min} is 2.

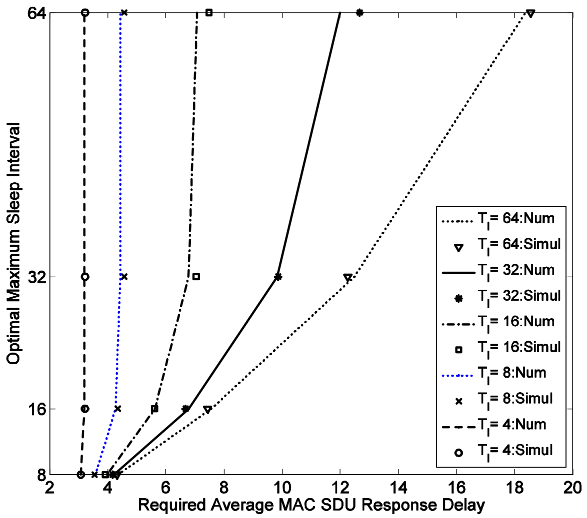

Fig. 9. T_{max} and $E[R]$ when T_{min} is 4.

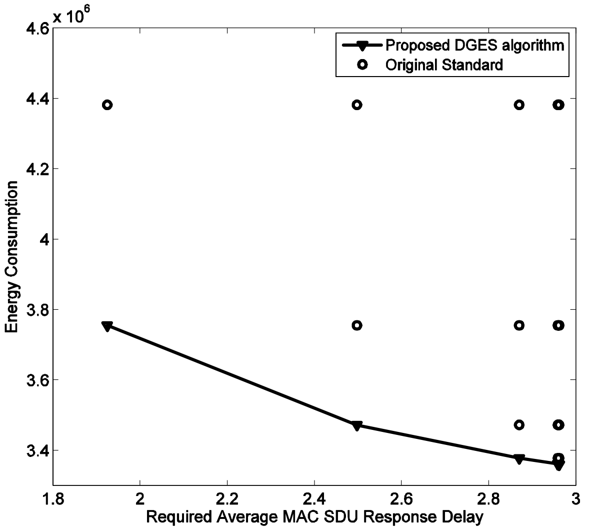

Fig. 10. $E[R]$ and Energy Consumption when T_{min} is 1 and T_I is 8.

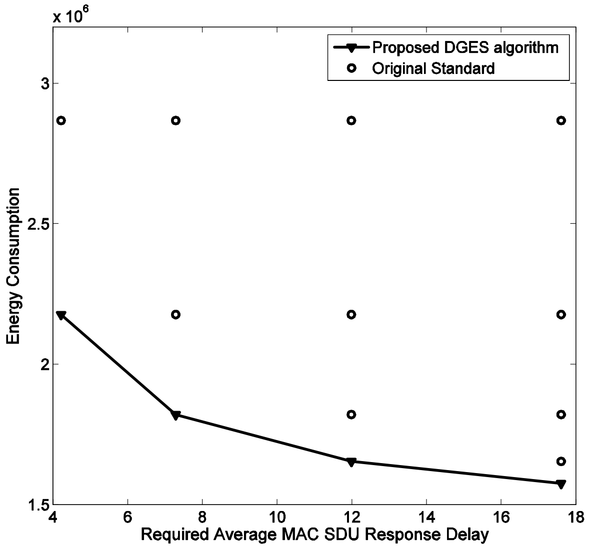

Fig. 11. $E[R]$ and Energy Consumption when T_{min} is 2 and T_I is 64.

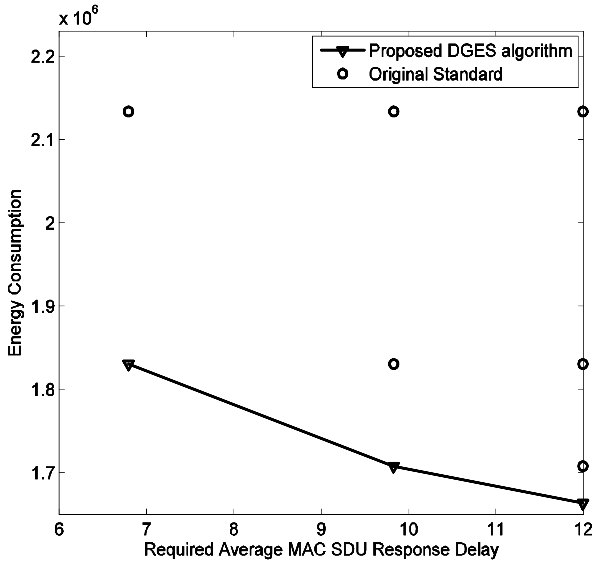

Fig. 12. ***E[R]*** **and Energy Consumption when T_{min} is 4 and T_I is 32.**

when the required $E\left[R\right]$ increases. Although the original IEEE 802.16e standard can achieve the same energy consumption with our proposed DGES algorithm, that possibility is low. Showing the same relationship between $E\left[R\right]$ and energy consumption, Fig. 11 is with $T_{min} = 2$ and $T_I = 64$ and Fig. 12 is with $T_{min} = 4$ and $T_I = 32$. In all these cases, our algorithm achieves the minimum energy consumption. The improvement made by our algorithm is potentially large when T_{min} and T_I increase. In the worst case, our proposed DGES energy consumption can save up to 42% of energy consumption. It can be summarized that, the energy consumed by our algorithm is minimized.

VI. CONCLUSION

Besides energy consumption, MAC SDU response delay is another important performance metric in IEEE 802.16e, especially for delay-sensitive applications. Because of the tradeoff relationship between energy consumption and MAC SDU response delay, we cannot improve both simultaneously. This paper deals with the problem of how to minimize energy consumption with a given average MAC SDU response delay.

Energy consumption and MAC SDU response delay are affected directly by T_{min} and T_{max} in sleep-mode operation of MSSs. In this paper, we first proposed a numerical model describing the relationship between T_{max} and MAC SDU response delay when T_{min} has been determined. Then, based on this numerical mode, we proposed DGES algorithm to minimize energy consumption with a given MAC SDU response delay by finding optimal T_{max} under fixed T_{min}. Thus, we effectively extended the lifetime of MSSs. Finally, we verified both our proposed numerical model and our proposed DGES algorithm by simulations. The pretty match between numerical results and simulation results shows that the methodology and the analysis in this paper provide useful guidance for energy saving while considering MAC SDU response delay.

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