An Enhanced Energy Saving Mechanism in IEEE 802.16e

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***Abstract*—In IEEE 802.16e, the energy saving mechanism is an important problem. Excessive listening operations in sleep-mode will waste a lot of energy and shorten the lifetime of a Mobile Subscriber Station (MSS). In this paper, we propose an enhanced energy saving mechanism to overcome this problem. An embedded Markov chain model is adopted to analyze the enhanced energy saving mechanism analytically. Meanwhile, a closed-form expression of the average energy consumption in the sleep-mode for the suggested mechanism is presented. We evaluate and validate the suggested scheme via analytical results and simulation results. Simulation results illustrate that the proposed mechanism can obtain better effects of energy conservation to minimize MSS power usage and to extend the lifetime of MSS effectively while not compromise the performance of Service Data Unit (SDU) response time.**

Key words: IEEE 802.16e; Energy Conservation; Sleep-model.

I. INTRODUCTION

As a promising emerging technology of a fixed Broadband Wireless Access (BWA) industry, the IEEE 802.16 [1] provides high-rate network connections to stationary sites [2]. The original IEEE 802.16 standard only supports fixed BWA system in which Subscriber Stations (SSs) are in fixed locations. To fill the gap between very high data rate wireless local area networks and very high mobility cellular systems, the emerging IEEE 802.16e standard [3] enhances the original standard with mobility so that Mobile Subscriber Stations (MSSs) can move during services. It will support fixed and mobile services for both enterprise and consumer markets. Mobility of MSSs implies that energy saving becomes an issue so that lifetime of MSS can be extended before re-charging. The IEEE 802.16e protocol proposes a sleep-mode operation to save the energy. Yang Xiao [4] analytically modeled the sleep-mode scheme, which is suggested in the IEEE 802.16e wireless Metropolitan Area Network (MAN). Jun-Bae Seo *et al*. [5] investigated the queuing behavior of the sleep mode operation in IEEE 802.16e for conserving the power of a MSS in terms of the dropping probability and the mean waiting times of the queue of Base Station (BS). Neung-Hyung Lee *et al.* [6] proposed a sleep mode interval control algorithm that considers downlink traffic pattern and terminal mobility to maximize energy-efficiency. In this paper, we denote the Energy Saving Mechanism (ESM) suggested in the IEEE 802.16e as ESM. The ESM requires that the initial-sleep window is the minimum sleep interval. This will result in excessive listening intervals, which consume more energy, when traffic is low.

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In this paper, we propose an Enhanced Energy Saving Mechanism (EESM) for IEEE 802.16e to overcome this problem and promote the energy conserving effects. We apply an embedded Markov chain to analyze our suggested energy saving mechanism. We denote the suggested scheme as EESM. By simulations, we compare the effects of energy conservation, the average sleep lengths of a MSS and the Media Access Control (MAC) Service Data Unit (SDUs) response time between the EESM and the former ESM.

The rest of this paper is organized as follows. In Section II, the sleep-mode operation for the energy saving in the IEEE 802.16e standard is introduced. In Section III, a Markov model for the enhanced energy saving mechanism (EESM) is presented. We provide a performance evaluation for the suggested scheme via analytical results and validated with simulations in Section IV. Meanwhile, the performance between the original mechanism ESM and the enhanced one EESM are compared. Finally, we draw conclusions in Section V.

II. OVERVIEW OF SLEEP MODE IN IEEE 802.16E

In the IEEE 802.16e standard, there are three types of Power Saving Classes recommended for connections of UGS, RT-VR, NRT-VR and BE type. As in [4, 5], only the power saving class for connections of BE, NRT-VR type is considered in this paper. In the scenario, a MSS has two modes: wake-mode and sleep-mode, shown in Fig.1. Before entering the sleep mode, the MSS in the wake-mode sends the sleep request message to the BS and waits for BS's approval before goes to sleep. After receiving the sleep response message which notifies the sleep request of the MSS approval, the MSS enters the sleep-mode. The sleep request message includes some parameters as follows: initial sleep window, listening window, final sleep window base and so on. The sleep response message includes some parameters, such as the start time of sleep-mode, the minimum sleep interval T_{min}, the maximum sleep interval T_{max} and the listening interval are presented in units of MAC frames. Such a procedure should be negotiated beforehand between the MSS and the BS. The MSS gets sleep for an interval, and then temporarily wakes up a short interval, called listening interval, to listen the traffic indication message broadcasted from the BS, and the message includes information about MSSs to whom the BS has SDUs waited. If there are SDUs for the MSS, the MSS goes to wakeup mode. Otherwise, the MSS is still in the sleep-mode and continues sleep for another interval. The MSS keeps performing the above procedure until it goes to the

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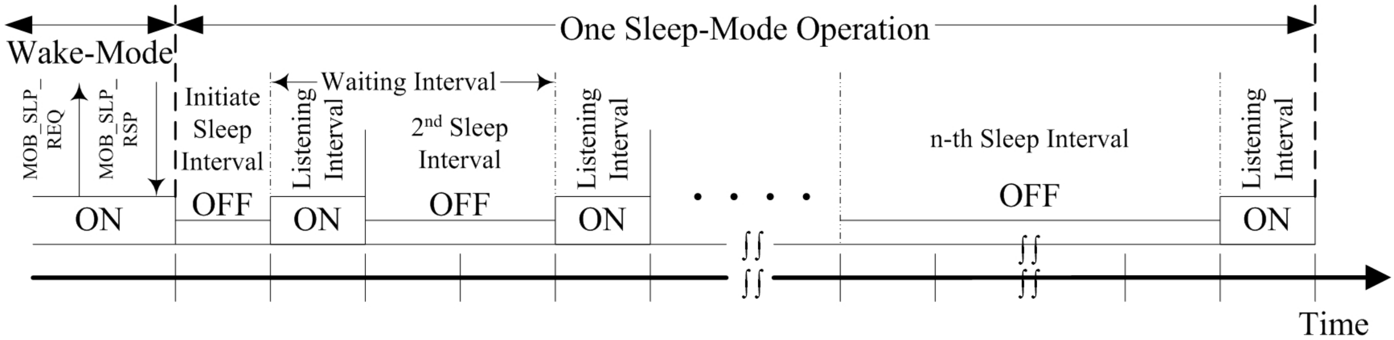

Figure 1. Sleep Mode Operation in IEEE 802.16e

wake-mode. We call the procedure from entering sleep-mode to exit sleep-mode as one sleep-mode operation in a MSS, shown in Fig.1. In the 802.16e [3], T_{min} is used as the first sleep interval when a MSS enters the sleep-mode. Then each sleep interval is doubled ($2^j T_{min}$), until T_{max} is reached, and then the sleep interval keeps T_{max}, where j denotes the j^{th} sleep interval. During each sleep interval, a MSS can turn off its transmitter and receiver unit in order to conserve the energy. Furthermore, the MSS can terminate the sleep-mode if there is an out-going SDU, mostly because of the user's manual interaction [4]. For more detailed operation of the sleep mode, refer to [3].

III. ANALYTICAL MODELS

According to above description, we can find that the minimum sleep interval is always used as the initiate sleep interval when a MSS enters sleep-mode every time. It is obvious that there are a lot of listening intervals in sleep-mode when the traffic is low. These listening operations consume much energy and shorten the lifetime of MSS before re-charging. Therefore, we propose an enhanced energy saving mechanism, namely EESM, to minimize MSS power usage and extend the lifetime of MSS.

A. The Enhanced Energy Saving Mechanism (EESM)

Differing from ESM, the initiate sleep interval is not the minimum sleep interval T_{min} in EESM. A MSS uses half of the last sleep interval when it exits from the previous sleep-mode operation as the initiate sleep interval in next sleep-mode operation. When the initiate sleep interval is less than T_{min}, the initiate sleep interval should be equal to T_{min}. BS can be informed of the initiate sleep interval of MSS in the sleep request message sent by a MSS. When traffic is low the inter-SDU arrival interval is large and EESM can effectively decrease the number of listening intervals in one sleep-mode operation.

The main idea of EESM is to reduce the listening operation as few as possible while to monitor the arrival of SDUs effectively. There is no any change needed in the IEEE 802.16e standard for EESM. We only set the 'initiate-sleep window' field of MOP_SLP_REQ message as half of the last sleep interval of the previous sleep-mode operation. The EESM algorithm can be well kept the compatibility with IEEE 802.16e standard.

B. Embedded Markov Model for EESM

As in [4, 5], we also assume that the SDU, dedicated for a MSS, arrival process from network to a BS follows a Possion process with rate λ. Then the inter-SDU arrival time follows an exponential distribution with mean $1/\lambda$. In addition, we assume that the listening interval is a fixed length, during which period the BS sends traffic indication message broadcasted. We define a waiting interval which is denoted by W_i to be a sum of a sleep interval and a listening interval as follows.

$$W_i = T_i + T_L = 2^i T_{min} + T_L \qquad 1 \le i \le N_{max} \tag{1}$$

Where $N_{max} = \log_2^{(Tmax/Tmin)}$. Because half of the last sleep interval is used as the initiate sleep interval. There are N_{max} cases for the initiate state. Let I_j denote the initiate sleep interval. It is expressed as follows.

$$I_j = T_j = 2^j T_{min}. \qquad 0 \le j \le N_{max}-1 \tag{2}$$

Let S_i ($1 \le i \le N_{max}$) denote the state that a MSS is on a waiting interval W_i. Meanwhile, let $\hat{S}_i$ denote the state that a MSS is on an initiate sleep interval I_i. So we can describe the states of a MSS, which is in the sleep-mode, and the state transitions by using an embedded Markov chain, shown in Fig.2. The transition probability from S_i to S_{i+1}, which is denoted by t_i, is the probability that there is no arriving SDU during a waiting interval W_i. It is expressed as

$$\Pr(S_{i+1} \mid S_i) = t_i = e^{-\lambda W_i}, \quad 1 \le i \le N_{max} \tag{3}$$

The transition probability from $\hat{S}_j$ to S_{j+1}, which is denoted by $\hat{t}_j$, is the probability that there is no arriving SDU during the initiate interval I_j. It is expressed as

$$\Pr(S_{j+1} \mid \hat{S}_j) = \hat{t}_j = e^{-\lambda I_j}, \quad 0 \le j \le N_{max}-1 \tag{4}$$

The transition probability from S_i to $\hat{S}_{i-1}$ is the probability that there are some arriving SDUs during a waiting interval W_i and the initiate sleep interval of the MSS is I_{i-1} in next sleep-mode

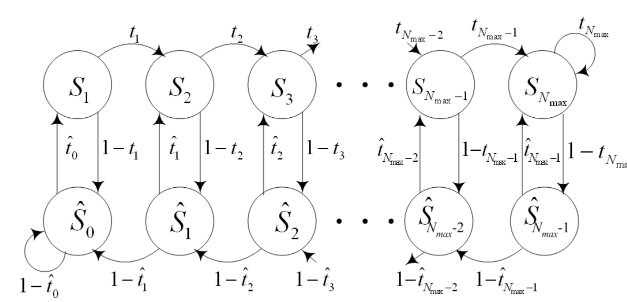

Figure 2. State Transition Model of EESM

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operation. It is expressed as

$$\Pr(\hat{S}_{i-1} \mid S_i) = 1 - t_i = 1 - e^{-\lambda W_i}, \ 1 \le i \le N_{max} \quad (5)$$

The transition probability from $\hat{S}_j$ to $\hat{S}_{j-1}$ is the probability that there are some arriving SDUs during an initiate sleep interval I_j and the initiate sleep interval of MSS is I_{j-1} in next sleep-mode operation. It is expressed as

$$\Pr(\hat{S}_{j-1} \mid \hat{S}_j) = 1 - \hat{t}_j = 1 - e^{-\lambda I_j}, \ 1 \le j \le N_{max}-1 \quad (6)$$

Note that during the listening interval following the initiate sleep interval, a serving BS only informs a MSS of the arriving SDUs in the initiate sleep interval. Furthermore, all the transition probabilities between other states are zero. According to Fig.2, the transition matrix $\boldsymbol{P}$ can be expressed as shown in (7) at the bottom of this page.

In this paper, we define T_s as the sleep length experienced by a MSS before it goes to the wake-mode. In order to calculate $E[T_s]$, the average sleep length of MSS, we model the state transitions between initiate sleep intervals as a Markov chain, shown in Fig. 3. Let SI_j denote the state that the initiate sleep interval is $2^j T_{min}$ ($0 \le j \le N_{max}-1$). The transition probability from SI_i to SI_j, which is denoted by φ_{ij}, is the probability that the initiate sleep interval of current sleep-mode is I_i and that of next sleep-mode is I_j. According to Fig. 3 and equation (7), we can obtain that

$$\varphi_{ij} = \Pr\left(SI_j \mid SI_i\right) = \begin{cases} 1-\hat{t}_i, & j = i-1 \\ \hat{t}_i\left(1-t_{j+1}\right), & j = i \\ \hat{t}_i t_{i+1} \cdots t_j \left(1-t_{j+1}\right), & i < j \le N_{\max}-2 \\ \hat{t}_i t_{i+1} \cdots t_{N_{\max}-1}, & j = N_{\max}-1 \\ 0, & \text{others} \end{cases} \quad (8)$$

where $1 \le i \le N_{\max}-2$. When i=0, the transition probability from SI_0 to other states is expressed as

$$\varphi_{0j} = \Pr\left(SI_j \mid SI_0\right) = \begin{cases} 1-\hat{t}_0 t_1, & j = 0 \\ \hat{t}_0 t_1 t_2 \cdots t_j \left(1-t_{j+1}\right), & 1 \le j \le N_{\max}-2 \\ \hat{t}_0 t_1 t_2 \cdots t_{N_{\max}-1}, & j = N_{\max}-1 \end{cases} \quad (9)$$

As a result, the state transition matrix $\boldsymbol{\Phi}$ of initiate sleep intervals can be expressed as

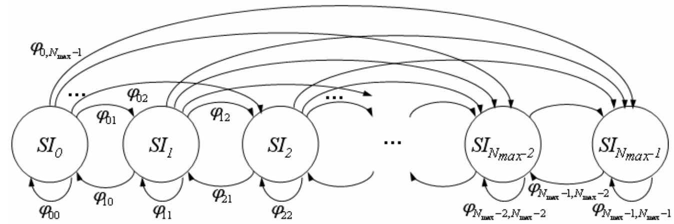

Figure 3. State Transition Model of Initiate Sleep Interval

$$\Phi = \begin{pmatrix} \varphi_{00} & \varphi_{01} & \varphi_{02} & \cdots & \varphi_{0,N_{\max}-2} & \varphi_{0,N_{\max}-1} \\ \varphi_{10} & \varphi_{11} & \varphi_{12} & \cdots & \varphi_{1,N_{\max}-2} & \varphi_{1,N_{\max}-1} \\ 0 & \varphi_{21} & \varphi_{22} & \cdots & \varphi_{2,N_{\max}-2} & \varphi_{2,N_{\max}-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \varphi_{N_{\max}-2,N_{\max}-2} & \varphi_{N_{\max}-2,N_{\max}-1} \\ 0 & 0 & 0 & \cdots & \varphi_{N_{\max}-1,N_{\max}-2} & \varphi_{N_{\max}-1,N_{\max}-1} \end{pmatrix} \quad (10)$$

Let $\bar{\pi} = \left\{\pi_{SI_0}, \pi_{SI_1}, \cdots, \pi_{SI_{N_{\max}-1}}\right\}$ be the steady-state probability. With $\bar{\pi} = \bar{\pi} * \Phi$ we can obtain each steady-state probability as

$$\pi_{SI_j} = \frac{\hat{t}_0 \prod_{k=1}^{j} t_k}{\prod_{k=1}^{j}\left(1-\hat{t}_k\right)} \pi_0, \qquad 1 \le j \le N_{\max}-1 \quad (11)$$

Using the normalized condition $\sum_{k=0}^{N_{\max}-1} \pi_{SI_k} = 1$, π_{SI_0} is obtained by

$$\pi_{SI_0} = \frac{1}{1 + \sum_{k=1}^{N_{\max}-1} \frac{\hat{t}_0 \prod_{i=1}^{k} t_i}{\prod_{i=1}^{k}\left(1-\hat{t}_i\right)}} \quad (12)$$

When the initiate sleep interval is I_j the average sleep length of MSS is

$$P = \begin{array}{c|cccccccccccc} & \hat{S}_0 & \hat{S}_1 & \hat{S}_2 & \cdots & \hat{S}_{N_{\max}-2} & \hat{S}_{N_{\max}-1} & S_1 & S_2 & S_3 & \cdots & S_{N_{\max}-1} & S_{N_{\max}} \\ \hline \hat{S}_0 & 1-\hat{t}_0 & 0 & 0 & \cdots & 0 & 0 & \hat{t}_0 & 0 & 0 & \cdots & 0 & 0 \\ \hat{S}_1 & 1-\hat{t}_1 & 0 & 0 & \cdots & 0 & 0 & 0 & \hat{t}_1 & 0 & \cdots & 0 & 0 \\ \hat{S}_2 & 0 & 1-\hat{t}_2 & 0 & \cdots & 0 & 0 & 0 & 0 & \hat{t}_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \hat{S}_{N_{\max}-1} & 0 & 0 & 0 & \cdots & 1-\hat{t}_{N_{\max}-1} & 0 & 0 & 0 & 0 & \cdots & 0 & \hat{t}_{N_{\max}-1} \\ S_1 & 1-t_1 & 0 & 0 & \cdots & 0 & 0 & 0 & t_1 & 0 & \cdots & 0 & 0 \\ S_2 & 0 & 1-t_2 & 0 & \cdots & 0 & 0 & 0 & 0 & t_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ S_{N_{\max}-1} & 0 & 0 & 0 & \cdots & 0 & 1-t_{N_{\max}-1} & 0 & 0 & 0 & 0 & 0 & t_{N_{\max}-1} \\ S_{N_{\max}} & 0 & 0 & 0 & \cdots & 0 & 0 & 1-t_{N_{\max}} & 0 & 0 & 0 & 0 & t_{N_{\max}} \end{array} \quad (7)$$

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$$E[T_s \mid SI_j] = \sum_{l=1}^{\infty}\left(\Pr\{\text{no arriving SDU in } l \text{ successive sleep intervals}\}\cdot \sum_{k=j}^{l+j} T_k\right)$$
$$= \sum_{l=1}^{\infty}\left(\Pr\{\text{no arriving SDU in } l \text{ successive sleep intervals}\}\cdot \sum_{k=j}^{l+j} 2^k T_{\min}\right)$$
$$= \sum_{m=j+2}^{N_{\max}-1}\left[\left(\sum_{i=j}^{m} 2^i T_{\min}\right)\hat{t}_j\left(1-t_m\right)\prod_{k=1}^{m-1} t_k\right] + 2^j T_{\min}\left(1-\hat{t}_j\right)$$
$$+3(j+1)T_{\min}\hat{t}_j\left(1-t_{j+1}\right) + \left(\sum_{i=j}^{N_{\max}} 2^i T_{\min} + 2^{N_{\max}} T_{\min}\sum_{k=1}^{\infty} k\right)\hat{t}_j \prod_{i=j+1}^{N_{\max}} t_i \quad (13)$$

Therefore, according to the full probability formula, we can obtain the average sleep length of MSS as follows.

$$E[T_s] = \sum_{j=0}^{N_{\max}-1} \Pr\{SI_j\} * E[T_s \mid SI_j] = \sum_{j=0}^{N_{\max}-1} \pi_{SI_j} E[T_s \mid SI_j] \quad (14)$$

Let E_S and E_L denote the energy consumption units per unit of time in the sleep interval and the listening interval, respectively. Adopting the same idea as calculating $E[T_s]$, when the initiate sleep interval is I_j, the average energy consumption of MSS in the sleep-mode is

$$E[\text{Energy} \mid SI_j] = \sum_{l=1}^{\infty}\left(\Pr\left\{\begin{matrix}\text{no arriving SDU in } l \\ \text{successive sleep intervals}\end{matrix}\right\}\cdot \sum_{k=j}^{l+j}\left(T_k E_S + T_L E_L\right)\right)$$
$$= E[T_s \mid SI_j]\cdot E_S + \left[\hat{t}_j\left(1-t_{1+j}\right) + \sum_{m=j+1}^{N_{\max}-1}\prod_{k=1}^{m}\hat{t}_j t_k\left(1-t_{m+1}\right)\right]\cdot T_L \cdot E_L \quad (15)$$

Therefore, according to the full probability formula, we can obtain the average energy consumption in the sleep mode as follows.

$$E[\text{Energy}] = \sum_{j=0}^{N_{\max}-1} \Pr\{SI_j\}\cdot E[\text{Energy} \mid SI_j] = \sum_{j=0}^{N_{\max}-1} \pi_{SI_j} E[\text{Energy} \mid SI_j]$$
$$= \sum_{j=0}^{N_{\max}-1} \pi_{SI_j}\left\{E[T_s \mid SI_j]E_S + \left[\hat{t}_j\left(1-t_{1+j}\right) + \sum_{m=j+1}^{N_{\max}-1}\prod_{k=1}^{m}\hat{t}_j t_k\left(1-t_{m+1}\right)\right]T_L E_L\right\} \quad (16)$$

IV. Performance Evaluation

We evaluate the EESM scheme with analytical results and validate the results by simulations. Meanwhile, we compare the effects of energy conservation, the average listening number $E[n]$, the average sleep lengths of MSS and the average response time of MAC SDU between the EESM and the ESM. In this paper, let $E[R]$ denote the average SDU response time which means from the time when the SDU arrives at the MAC layer of BS to the time it is listened by the MSS.

A. Simulation Validation

We conduct simulations to validate analytical results for EESM. The simulation parameters are the same as [4]. They are listed as follows: T_L=1 (unit time), T_{min}=1 (unit time), T_{max}=1024 (unit time), E_S=1 and E_L=10. In the mean time, an OFDMA frame length, the basic unit time, is 5ms. Fig. 4 shows both simulation results and analytical results of $E[T_S]$ over the SDU (or packet) arrival rate λ. As illustrated in the figure, the simulation results match analytical results pretty well. Due to size constraints, T_{min}=1 is only considered in following evaluations.

B. Performance Metrics of EESM Over T_{max}

Performance metrics ($E[n]$, $E[T_S]$, average energy consumption and $E[R]$) with different T_{max} over λ are shown in

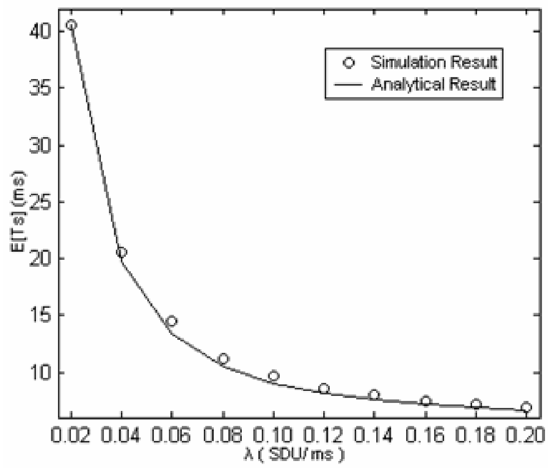

Figure 4. Simulation results vs. analytical results

Fig. 5. As illustrated in the figure, all performance metrics ($E[n]$, $E[T_S]$, average energy consumption and $E[R]$) decrease as the SDU arrival rate λ increases except that average sleep length with T_{max}=1. Meanwhile, $E[n]$ decreases as T_{max} increases under the same λ. Less listening intervals result in less energy consumption. On the other hand, $E[T_S]$ increases as T_{max} increases under the same λ. But it will bring out a larger SDU response time since a larger T_{max} value means longer sleep intervals can be used.

C. EESM vs. ESM Over T_{max}

Fig. 6, Fig. 7 and Fig. 8 compare performance metrics of EESM with ones of ESM over λ with T_{max}=4, T_{max}=8 and T_{max}=1024 respectively. From these figures, we see that performance difference between two schemes becomes smaller as the T_{max} decreases. When T_{max} is larger than 2, EESM experiences less average listening number $E[n]$ and consumes less energy than ESM. The average listening number difference of EESM and ESM is very distinct when T_{max}=1024. In this case, the average listening number of EESM is always kept below 2. In addition, the average SDU response time difference of EESM and ESM decreases as T_{max} value decreases. In these figures, the performance difference of EESM and ESM shortens as λ rises. It's reasonable that EESM has the same performance as ESM when λ is high.

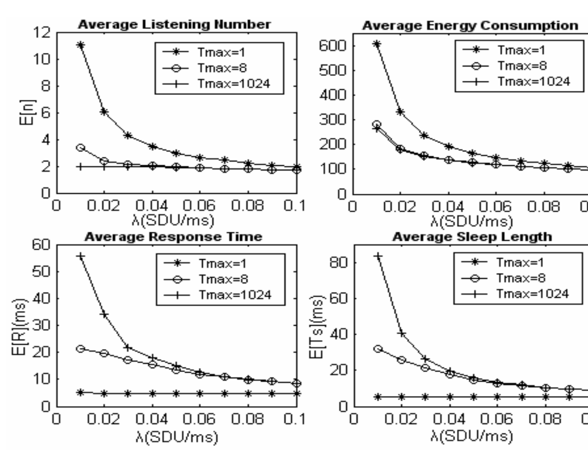

Figure 5. Performance metrics over λ with different T_{max}

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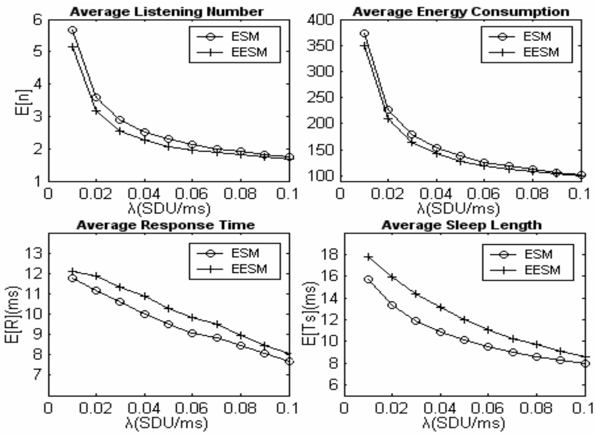

Figure 6. EESM vs. ESM (T_{max}=4)

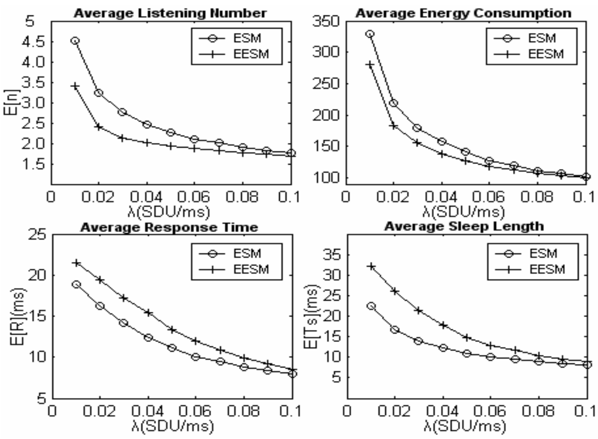

Figure 7. EESM vs. ESM (T_{max}=8)

The percentage of energy saved by EESM with different values of T_{max}, compared to ESM, is shown in Fig. 9. From this figure, we see that the energy conservation percentage increases as λ decreases. When λ is high the better or same energy conservation effects can still be achieved by EESM. In addition, the percentage of energy saved by EESM increases as the value of T_{max} increases since larger T_{max} means longer sleep interval can be used and more energy can be saved.

Although the SDU response time of EESM is larger than that of ESM, since only the power saving class for connection of BE, NRT-VR type is considered in this paper as [4, 5], a little increase of SDU response time is acceptable and tolerable for these connections. According to above analysis, we can get that EESM can obtain better effects of energy conservation than ESM while not compromise the performance of BE and NRT-VR connections.

V. CONCLUSION

In this paper, we proposed an enhanced energy saving mechanism for the emerging IEEE 802.16e standard. Differing from ESM, EESM uses half of the last sleep interval when it exits from the previous sleep-mode operation as the initiate sleep interval in next sleep-mode operation. We apply an embedded Markov chain model to analyze our suggested energy saving mechanism. A closed-form expression of the average energy consumption in the sleep-mode for the enhanced energy saving mechanism is presented. We evaluate the suggested scheme via analytical results and validate it with simulation results. Meanwhile, simulation results show that the proposed mechanism can obtain better effects of energy conservation than ESM to minimize MSS power usage and to extend the lifetime of MSS effectively.

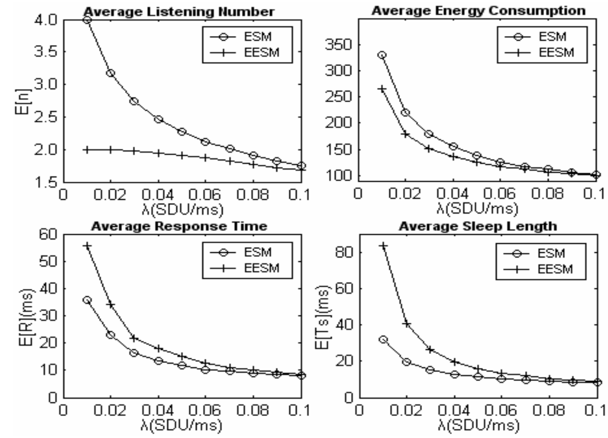

Figure 8. EESM vs. ESM (T_{max}=1024)

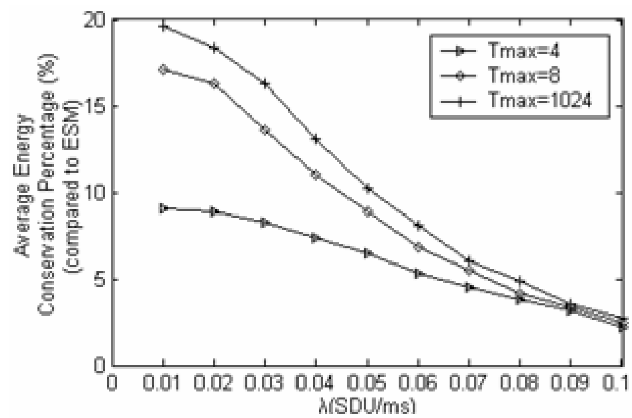

Figure 9. Average Energy Conservation Percentage

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