Energy Management in the IEEE 802.16e MAC

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***Abstract*— Energy management is an important component for the emerging standard IEEE 802.16e supporting mobility. In this paper, we characterize the standardized sleep mode in IEEE 802.16e. The comparison between our result and the simulation shows that our analytical model is accurate in evaluating the energy consumption and hence provides a potential guidance in efficiently managing energy.**

***Index Terms*— IEEE 802.16e, WiMAX, Wireless MAN, MAC, energy efficiency, sleep-mode.**

I. Introduction

The IEEE 802.16 standard (or WiMAX) [1] is an emerging broadband wireless access system for bridging the last mile, replacing costly wireline and also providing high speed multimedia services. The amendment 802.16e [2] adds mobility component for WiMAX and defines both physical and MAC layers for combined fixed and mobile operations in licensed bands. Due to the promising mobility capability in IEEE 802.16e, the mechanism in efficiently managing the limited energy is becoming very significant since a Mobile Subscriber Station (MSS) is generally powered by battery. For this, sleep mode operation is recently specified in the MAC protocol [2] [3].

Fig. 1 shows the wake mode and sleep mode of an MSS. Before entering the sleep mode, the MSS sends a request message to Base Station (BS) for the permission to transit into sleep mode. Upon receiving the response message from the BS with parameters initial-sleep window (T_{min}), final-sleep window (T_{max}) and listening window (L), the MSS enters into sleep mode. After a sleep mode, the MSS transits back to the wake mode again. As a consequence, the MSS alternatively stays in wake mode and sleep mode during its lifetime.

Now, we focus on the mechanism in the sleep mode. The duration of the first sleep interval T_1 is equal to the initial-sleep window T_{min}. After the first sleep interval, the MSS transits into listening state and listens to the traffic indication message MOB-TRF-IND broadcasting from BS. The message indicates whether there has been traffic addressed to the MSS during its sleep interval. If MOB-TRF-IND indicates a negative indication, then the MSS continues its sleep mode after the listening interval L. Otherwise, the MSS will return to wake mode. We term the sleep interval and its subsequent listening interval as a cycle.

If the MSS continues sleep mode, the next sleep-window starts from the end of the previous listening-window; and

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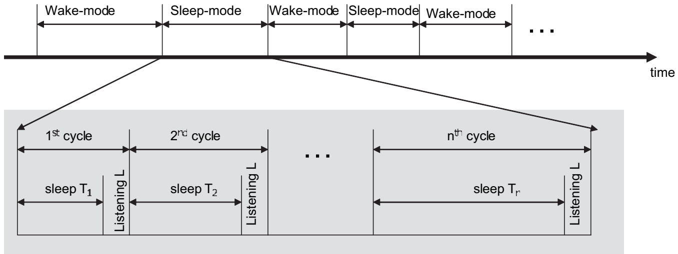

Fig. 1. Wake mode and sleep mode in IEEE 802.16e

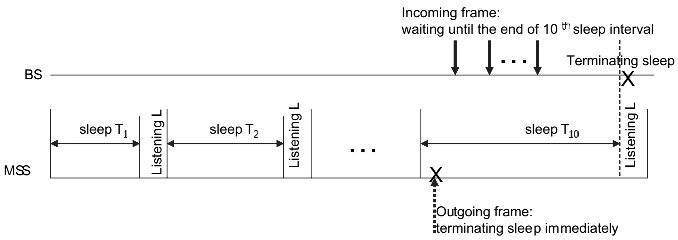

Fig. 2. Motivation

it shall double the preceding sleep interval. This process is repeated as long as the sleep interval does not exceed the final-sleep window T_{max}. When the MSS has reached T_{max}, it shall keep the sleep interval as fixed T_{max}. That is, the duration of sleep interval in the n^{th} cycle is given by

$$T_n = \begin{cases} T_{min}, & n = 1 \\ \min(2^{n-1}T_{min}, T_{max}), & n > 1 \end{cases} \qquad (1)$$

In case there are incoming frames [1] to a sleeping MSS, the MSS exits the sleep mode in the next listening interval. In contrast, if there are outgoing frames during the sleep interval, the sleep mode is terminated immediately. As a consequence, the instants in terminating sleep mode are different for different traffics. It is thus necessary and reasonable to differentiate the traffics in determining the sleep mode duration.

In [3], Xiao proposed a novel model to investigate the energy consumption in IEEE 802.16e by considering the message delivery from BS to MSS. In this paper, we will analyze the energy consumption by considering both the incoming frames and outgoing frames since the instants of terminating sleep mode by incoming or outgoing traffics are different. For instance, Fig. 2 shows a scenario with $T_{min} = L = 1$ and $T_{max} = 2^9 T_{min} = 512$. No incoming or outgoing frames arrive during the $1^{th}, 2^{nd}, \cdots, 9^{th}$ cycle. During the tenth sleep interval, there are a number of incoming frames; and an outgoing frame arrives in the first slot. In case the

[1] For a particular MSS $\mathcal{M}$, incoming frames refer to the packet flow sending from other MSSs or BS to $\mathcal{M}$; outgoing frames refers to the messages and data sending from $\mathcal{M}$ to other MSSs or BS.

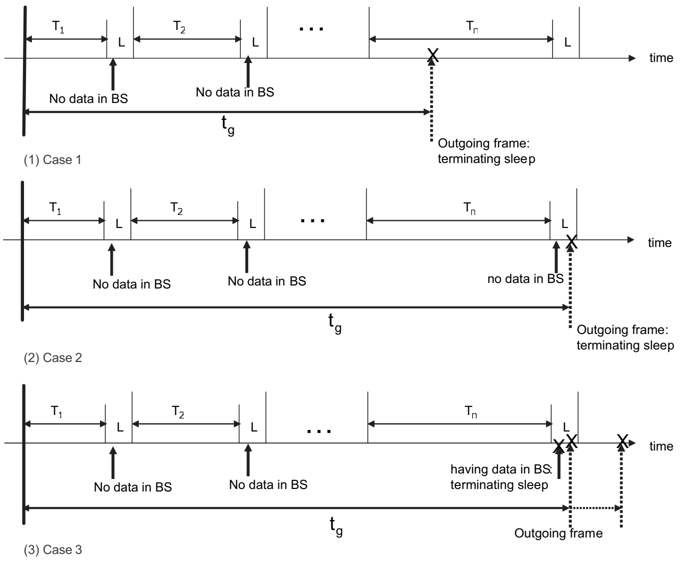

Fig. 3. System model

frame directions are not differentiated, all these frames will be temporarily stored until the sleep mode is terminated in the tenth listening interval. The duration of the sleep mode is $(T_1+L)+(T_2+L)+\cdots+(T_{10}+L)=1033$. However, due to the outgoing frame, the sleep mode is actually terminated immediately at the first slot of the tenth sleep window. Hence, the actual period of the sleep mode is $(T_1+L)+(T_2+L)+\cdots+(T_9+L)+1=521$. The overestimated error is $(1033-521)/521=98.3\%$. As a result, it is necessary to distinguish the incoming and outgoing traffics. This example motivates our study for differentiating traffics and performing complete evaluation of the energy management.

II. System Model

We assume that the incoming and the outgoing frames addressing to the MSS follow the Poisson processes with rate λ_c and λ_g, respectively. Then, the inter-arrival time of outgoing frame, t_g, follow the exponential distribution. Let $\lambda=\lambda_c+\lambda_g$ be the total arrival rate to the MSS. Let e_j denote the event that there is at least one incoming frame during the j^{th} sleep window plus its preceding listening window. Then, we have

$$Pr(e_j=false)=e^{-\lambda_c(T_j+L)};\quad j=1,2,\cdots \tag{2}$$

Under the condition that the MSS terminates the sleep mode during the n^{th} cycle, we distinguish three possibilities as shown in Fig. 3. Accordingly, we denote $E_n^{(k)}$ as the consumed energy during the case $k(k=1,2,3)$ provided that the MSS terminates the sleep mode in the n^{th} cycle. In addition, let $\phi_n^{(k)}$ be the probability for case $k(k=1,2,3)$ under the condition that the MSS terminates the sleep mode in the n^{th} cycle. The consumed energy during a sleep mode is expressed as

$$Energy=\sum_{n=1}^{\infty}\sum_{k=1}^{3}\overline{E_n^{(k)}}\phi_n^{(k)} \tag{3}$$

where $\overline{X}$ denotes the average value of the random variable X. Let E_S and E_L denote the consumed energy units per unit time in the sleep interval and the listening interval, respectively.

1) Case (1) in Fig. 3: In the first case, there is an outgoing frame terminating the sleep mode during the n^{th} sleep interval. This implies that there are no packets during the $j^{th}(j=1,2,\cdots,n-1)$ sleep interval. In addition, t_g should be greater than $\sum_{j=1}^{n-1}T_j+(n-1)L$ and concurrently less than $\sum_{j=1}^{n}T_j+(n-1)L$. For the sake of presentation, we denote

$$W_n=\sum_{j=1}^{n}(T_j+L) \tag{4}$$

In such case, we define an alternative random variable $t_g^{'}$ satisfying

$$t_g^{'}=\begin{cases} t_g, & W_{n-1}<t_g<W_{n-1}+T_n\\ 0, & \text{otherwise.}\end{cases} \tag{5}$$

Then, the average value of $t_g^{'}$ is given by

$$\overline{t_g^{'}}=\frac{\int_{W_{n-1}}^{W_{n-1}+T_n}\lambda_g x e^{-\lambda_g x}dx}{\int_{W_{n-1}}^{W_{n-1}+T_n}\lambda_g e^{-\lambda_g x}dx} =\frac{(W_{n-1}+\frac{1}{\lambda_g})(1-e^{-\lambda_g T_n})-T_n e^{-\lambda_g T_n}}{1-e^{-\lambda_g T_n}} \tag{6}$$

The energy for the first case is expressed as

$$E_n^{(1)}=\sum_{j=1}^{n-1}T_jE_S+(n-1)LE_L+\left[t_g^{'}-\sum_{j=1}^{n-1}T_j-(n-1)L\right]E_S =[t_g^{'}-(n-1)L]E_S+(n-1)LE_L \tag{7}$$

Hence, the average energy consumption is given by

$$\overline{E_n^{(1)}}=\left[\overline{t_g^{'}}-(n-1)L\right]E_S+(n-1)LE_L \tag{8}$$

where $\overline{t_g^{'}}$ is given in (6). The probability for the first situation is given by

$$\phi_n^{(1)}=Pr(W_{n-1}<t_g<W_{n-1}+T_n)\prod_{j=1}^{n-1}Pr(e_j=false) =e^{-(\lambda_g+\lambda_c)W_{n-1}}(1-e^{-\lambda_g T_n}) \tag{9}$$

2) Case (2) in Fig. 3: In the second case, there is an outgoing frame terminating the sleep mode during the n^{th} listening interval. This indicates that there are no packets during the $j^{th}(j=1,2,\cdots,n)$ sleep interval. In addition, t_g should be greater than $W_{n-1}+T_n(=W_n-L)$ and also less than W_n. In such case, we denote an alternative random variable $t_g^{'}$ satisfying

$$t_g^{'}=\begin{cases} t_g, & W_n-L<t_g<W_n\\ 0, & \text{otherwise.}\end{cases} \tag{10}$$

Then, the average value of $t_g^{'}$ is given by

$$\overline{t_g^{'}}=\frac{\int_{W_n-L}^{W_n}\lambda_g x e^{-\lambda_g x}dx}{\int_{W_n-L}^{W_n}\lambda_g e^{-\lambda_g x}dx} =\frac{(W_n+\frac{1}{\lambda_g})(e^{\lambda_g L}-1)-Le^{-\lambda_g L}}{e^{\lambda_g L}-1} \tag{11}$$

The energy for the second case is expressed as

$$E_n^{(2)} = \sum_{j=1}^{n} T_j E_S + (n-1)LE_L + \left[t_g' - \sum_{j=1}^{n} T_j - (n-1)L \right] E_L = \sum_{j=1}^{n} T_j E_S + \left[t_g' - \sum_{j=1}^{n} T_j \right] E_L \quad (12)$$

Hence, the average energy consumption is given by

$$\overline{E_n^{(2)}} = \sum_{j=1}^{n} T_j E_S + \left[\overline{t_g'} - \sum_{j=1}^{n} T_j \right] E_L \quad (13)$$

where $\overline{t_g'}$ is given in (11). The probability for the second situation is given by

$$\phi_n^{(2)} = Pr(W_n - L < t_g < W_n) \prod_{j=1}^{n} Pr(e_j = false) = e^{-(\lambda_g+\lambda_c)W_n} \left(e^{\lambda_g L} - 1 \right) \quad (14)$$

3) Case (3) in Fig. 3: As showing in the third illustration in Fig. 3, there are incoming packets during the n^{th} sleeping interval and temporarily buffering in BS. Moreover, during this sleep interval T_n, there is no outgoing frames. Upon the n^{th} sleeping completion, the MSS transits into the listening state and will receive the broadcast message MOB-TRF-IND with positive indication, and then terminate the sleep mode. Thus, the energy is given by

$$E_n^{(3)} = \overline{E_n^{(3)}} = \sum_{j=1}^{n} T_j E_S + nLE_L \quad (15)$$

The probability for this situation is given by

$$\phi_n^{(3)} = Pr(t_g > \sum_{j=1}^{n} T_j + (n-1)L) \cdot \prod_{j=1}^{n-1} Pr(e_j = false) Pr(e_n = true) = e^{-\lambda_g T_n} \left[1 - e^{-\lambda_c (T_n + L)} \right] e^{-(\lambda_c+\lambda_g)W_{n-1}} \quad (16)$$

Substituting (8) (9) (13) (14) (15) (16) into (3), we can calculate the power consumption during the sleep mode.

III. Numerical Results and Conclusions

We choose the following parameters: $E_S = 1$, $E_L = 10$ and $L = 1$. Fig. 4 shows the energy in terms of λ with different T_{min} and T_{max}. We have developed a simulation program to validate the analytical model. It is clear that the analysis and the simulation match each other very well. The comparison indicates that the consumed energy may be greatly overestimated if the different consequences of incoming and outgoing frames are not identified. Fig. 5 shows the energy in terms of different ratio λ_g/λ_c with fixed $\lambda = 0.05$. The comparison shows that the consumed energy indeed varies with the different frame directions. This is because, with more outgoing frames, the sleep mode is terminated instantaneously by outgoing frames with higher probability, leading to shorter sleep mode duration and consequently less energy consumption during sleep mode. This will eventually result in higher energy consumption during MSS's lifetime.

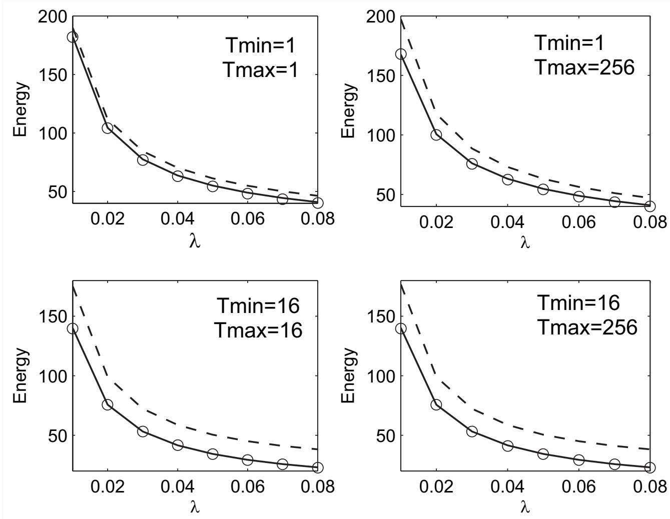

Fig. 4. Energy consumption in terms of λ ($\lambda_g = \lambda_c = \lambda/2$). Solid line: analysis (differentiating frame directions); dashed line: analysis (without differentiating frame directions); symbol: simulation.

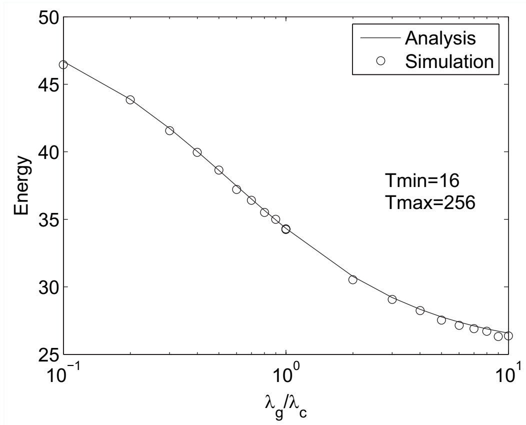

Fig. 5. Energy consumption in terms of λ_g/λ_c ($\lambda = 0.05$).

In conclusion, we proposed an analytical model to evaluate the energy management in the IEEE 802.16e Wireless MAN. The analysis has been validated by the simulation. The methodology as well as the results in this paper provide a potential guidance in efficiently managing energy.

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References

[1] IEEE 802.16-2001, IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems, Apr. 2002.
[2] IEEE 802.16e/D5-2004, Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems - Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, Nov. 2004.
[3] Y. Xiao, "Energy saving mechanism in the IEEE 802.16e wireless MAN," *IEEE Commun. Lett.*, vol. 9, pp. 595-597, July 2005.