A Novel Energy Saving Algorithm with Frame Response Delay Constraint in IEEE 802.16e

Dinh Thi Thuy NGA, Student Member, MinGon KIM, and Minho KANG, Nonmembers

SUMMARY Sleep-mode operation of a Mobile Subscriber Station (MSS) in IEEE 802.16e effectively saves energy consumption; however, it induces frame response delay. In this letter, we propose an algorithm to quickly find the optimal value of the final sleep interval in sleep-mode in order to minimize energy consumption with respect to a given frame response delay constraint. The validations of our proposed algorithm through analytical results and simulation results suggest that our algorithm provide a potential guidance to energy saving.

key words: IEEE 802.16e, sleep-mode, energy saving

1. Introduction

The original IEEE 802.16e standard defines a common Medium Access Control (MAC) to support only Broadband Wireless Access (BWA) networks in which locations of Subscriber Station (SS) are fixed [1], [2]. The amendment of IEEE 802.16e standard introduces the concept of sleep-mode operation to support mobility of MSSs, so that the MSSs can move during their service time [3], [4]. Mobility of MSSs means that energy saving becomes an important issue and that the lifetimes of MSSs can be extended effectively before being recharged.

There are three types of Power Saving Classes in IEEE 802.16e standard [1]–[4]. In this letter, we only consider Power Saving Classes type I, which is recommended for connections of BE, NRT-VR type as in [5], [7]. Figure 1 shows the operation of a MSS. The operation consists of wake-modes and sleep-modes. The sleep-mode includes sleep cycles; each is composed of a sleep interval and a listening interval. Before MSS goes to sleep-mode, it has to send a sleep request message to its Base Station (BS) to ask for permission. After getting sleep response message from BS with some parameters such as initial sleep interval, $T_{min}$, final sleep interval, $T_{max}$, and listening interval, $L$, the MSS goes to sleep-mode. The first sleep interval, $T_1$, is equal to $T_{min}$. After $T_1$, MSS transits to listening state for the duration of $L$ to check traffic indication massage from BS. If the message indicates a negative indication, meaning there is no traffic addressed to MSS during its sleep time, MSS continues to be in sleep-mode after $L$. The second sleep interval $T_2$ equals to $2T_{min}$. After $T_2$, MSS transits to listening state again. This procedure is repeated and the current sleep interval doubles its previous sleep interval until $T_{max}$ is reached.

The sleep interval is $T_{max}$, from that time, until the MSS receives positive indication from BS. Furthermore, the MSS transits to wake-mode whenever there is an outgoing frame or user’s manual interaction.

Sleep-mode operation for the power saving is one of the most important features for MSSs to extend their lifetimes. There have been several studies on sleep-mode operation. Yang Xiao analytically modeled sleep-mode operation in IEEE 802.16e [5]. Yan Zhang proposed an analytical model to evaluate energy management in IEEE 802.16e Wireless MAN [6]. In [7], 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 [8], the authors used a semi-Markov chain to derive packet delay and average power consumption of sleeping, listening, and waking-up states. Junfeng XIAO changed the value of initial sleep interval at low arrival rate to reduce energy consumption [9]. Although sleep-mode saves energy consumption, it causes frame response delay due to the arriving of MAC frames during MSSs’ sleeping time. Therefore, frame response delay is another key performance metric. Relationship between energy consumption and frame response delay is also mentioned in [7]: however, no researcher has concerned about minimizing energy consumption while taking frame response delay into consideration. In this letter, we deal with this problem. With a given constraint of frame response delay and with $T_{min}$ having been determined, we first evaluate the range of average frame response delay. Then, we propose a simple but effective algorithm to find the optimal value of $T_{max}$ which minimizes energy consumption.

The rest of this letter is organized as followed. In
Sect. 2, we present our proposed algorithm and its numerical analysis. In Sect. 3, we present performance evaluation through analytical results and simulations results. Finally, Sect. 4 is our conclusion.

2. Proposed Algorithm

$T_{\text{min}}$ and $T_{\text{max}}$ are important factors to reduce energy consumption in sleep-mode. The energy consumption decreases when either $T_{\text{min}}$ or $T_{\text{max}}$ increases; however, frame response delay will increase [5]. We can not improve both energy consumption and frame response delay simultaneously [6]. Our proposed algorithm minimizes energy consumption with given frame response delay constraint when $T_{\text{min}}$ has been determined.

2.1 Numerical Analysis

This section presents the foundation of our proposed algorithm. First, we point out that the average frame response delay has upper bound and lower bound with $T_{\text{min}}$ having been determined. Then, we propose our algorithm to find optimal value of $T_{\text{max}}$.

Let $n$ be the number of sleep intervals before a MSS goes to wake-mode, $\lambda$ be the arrival rate of customer to a MSS, $T_j$ be the sleep interval in sleep cycle $j$ and $L$ be the listening interval. Assume that the arrival rate to a MSS follows Poisson distribution. By [5], the probability that MAC frames arrive to a MSS only in sleep cycle $j$ is

$$P(n = j) = e^{-\lambda T_j} \left( 1 - e^{-\lambda (T_j + L)} \right)$$  \hfill (1)

Frame response delay performance metric is represented by an average frame response delay. Let $R$ be the frame response delay. Based on [5], average frame response delay is

$$E[R] = \sum_{j=1}^{\infty} P(n = j) \frac{T_j + L}{2}$$  \hfill (2)

Since $T_j \geq T_{\text{min}}$ with $j \geq 1$, we have

$$E[R] \geq \frac{T_{\text{min}} + L}{2}$$  \hfill (3)

Therefore, the lower bound of $E[R]$ is

$$E[R]_{\text{min}} = \frac{T_{\text{min}} + L}{2}$$  \hfill (4)

Let $M$ be the integer that satisfies

$$2^{M-1}T_{\text{min}} = T_{\text{max}}$$  \hfill (5)

The $j$-th sleep interval is expressed as

$$T_j = \begin{cases} 2^{j-1}T_{\text{min}} & \text{with } j < M \\ T_{\text{max}} & \text{otherwise} \end{cases}$$  \hfill (6)

(2) can be rewritten as

$$E[R] = \frac{L}{2} \sum_{j=1}^{\infty} \Pr(n = j) + \sum_{j=1}^{M-1} \Pr(n = j) \frac{T_j + \frac{T_{\text{max}}}{2}}{2} + \sum_{j=M}^{\infty} \Pr(n = j)$$

$$= \frac{L}{2} + \sum_{j=1}^{M-1} \Pr(n = j) \frac{T_j + \frac{T_{\text{max}}}{2}}{2} \sum_{j=M}^{\infty} \Pr(n = j)$$  \hfill (7)

Equality (7) implies that $E[R]$ is a non-decreasing function of $T_{\text{max}}$. First, $E[R]$ increases when $T_{\text{max}}$ increases. However, when $T_{\text{max}}$ reaches certain value, $E[R]$ stops increasing. The reason is that when $T_{\text{max}}$ is large enough, $M$ also increases but the probabilities calculated by (1) go to zero. This makes $E[R]$ stays constant. This value of $E[R]$ is its upper bound, called $E[R]_{\text{max}}$. We can calculate this value by calculating (7) with different values of $M$ and $T_{\text{max}}$ by (5) until $E[R]$ stops increasing. Next, we derive the formula showing the relationship between $E[R]$ and $T_{\text{max}}$ when $E[R]$ lies in $[E[R]_{\text{min}}, E[R]_{\text{max}}]$.

Based on (1), $P(n = j)$ is expressed as

$$P(n = j) = \begin{cases} e^{-(\frac{1}{2} T_{\text{max}} + L)} e^{-\lambda (2^{j-1} T_{\text{min}} + jL)} \left( 1 - e^{-\lambda (2^{j-1} T_{\text{min}} + jL)} \right) ; j < M \\ e^{-(\frac{1}{2} T_{\text{max}} + L)} \left( 1 - e^{-\lambda (2^{j-1} T_{\text{min}} + jL)} \right) ; j \geq M \end{cases}$$  \hfill (8)

We have

$$S = \sum_{j=1}^{M-1} \Pr(n = j) \frac{T_j}{2} = T_{\text{min}} e^{\frac{1}{2} (T_{\text{max}} + L)} \sum_{j=1}^{M-1} 2^{j-2} e^{-\lambda (2^{j-1} T_{\text{min}} + jL)} \left( 1 - e^{-\lambda (2^{j-1} T_{\text{min}} + jL)} \right)$$  \hfill (9)

and

$$\frac{T_{\text{max}}}{2} \sum_{j=M}^{\infty} \Pr(n = j) = \frac{T_{\text{max}}}{2} e^{-\lambda (2^{M-1} T_{\text{min}} + M L)}$$  \hfill (10)

Replace (9) and (10) into (7)

$$E[R] = \frac{L}{2} + S + \frac{T_{\text{max}}}{2} e^{-\lambda (2^{M-1} T_{\text{min}} + M L)}$$  \hfill (11)

$T_{\text{max}}$ is obtained from (11) as followed

$$T_{\text{max}} = \frac{2E[R] - 2S - L}{e^{-\lambda (2^{M-1} T_{\text{min}} + M L)}}$$  \hfill (12)

where $S$ is calculated by (9).

If $E[R] < E[R]_{\text{min}}$, there is no solution for $T_{\text{max}}$ because $E[R]$’s being lower than $E[R]_{\text{min}}$ makes the value of $T_{\text{max}}$ calculated by (12) lower than zero. On the other hand, if $E[R] \geq E[R]_{\text{max}}$, any $T_{\text{max}}$ satisfying $T_{\text{max}} \geq T_{\text{min}}$ will satisfy the frame response delay condition. These values of $E[R]$ make the numerator in (12) equal to zero. When $E[R]$ lies in $[E[R]_{\text{min}}, E[R]_{\text{max}})$, $E[R]$ is an increasing function of $T_{\text{max}}$; therefore, there will be a unique $T_{\text{max}}$ corresponding to each $E[R]$. $T_{\text{max}}$ calculated by (12) guarantees that energy consumption is minimized because if we further increase $T_{\text{max}}$ to reduce energy consumption, $E[R]$ will exceed its limitation. Hence, $T_{\text{max}}$ calculated by (12) is the
optimal value in terms of energy consumption. In addition, by (12), \( T_{\text{max}} \) is determined if \( E[R], \lambda, T_{\text{min}}, M \) and \( L \) are known. \( M \) depends on \( T_{\text{min}} \) and \( T_{\text{max}} \) by (5). The next section describes our proposed algorithm to find \( T_{\text{max}} \) based on the set of \((E[R], T_{\text{min}}, \lambda, L)\).

2.2 Energy Saving with Delay Constraint Algorithm

Since \( T_{\text{max}} = 2^{M-1}T_{\text{min}} \), we can determine \( T_{\text{max}} \) based on (12) by the following steps

Step 1: Find \( E[R]_{\text{min}} \) by (4).

Step 2: Find \( E[R]_{\text{max}} \) by increase \( M \) in (7) until \( E[R] \) does not change.

Step 3: If \((E[R]<E[R]_{\text{min}})\)

No \( T_{\text{max}} \).

Else

If \( (E[R] \geq E[R]_{\text{max}}) \)

\( T_{\text{max}} \geq T_{\text{min}} \).

Else

Go to Step 4.

Step 4: Assign \( M = 1 \).

Step 5: Find \( T_{\text{max}1} = 2^{M-1}T_{\text{min}} \).

Step 6: Find \( T_{\text{max}2} \) by (12).

Step 7: Compare \( T_{\text{max}1} \) and \( T_{\text{max}2} \).

If \(|T_{\text{max}1} - T_{\text{max}2}|/T_{\text{max}1} < 0.001\)

Go to Step 9.

Else

Go to Step 8.

Step 8: \( M = M + 1 \) and go back to Step 5.

Step 9: Calculate \( T_{\text{max}} = 2^{M-1}T_{\text{min}} \).

When \( E[R]_{\text{min}} \) and \( E[R]_{\text{max}} \) are found by Step 1 and Step 2, the remaining steps are illustrated in Fig. 2.

3. Performance Evaluation

This section evaluates the performance of our proposed algorithm. Let \( E_S \) and \( E_L \) are energy consumption per time units in sleep interval and listening interval. The arrival rate to a MSS is assumed to follow Poisson distribution with a rate \( \lambda = 1 \). Other parameters are assigned as follows: \( L = 1 \), \( E_S = 1 \) and \( E_L = 10 \). The simulation time is 1,000,000 CPU sec, and results are the average values from 20 different simulation runs with 20 different values of seeds.

Figure 3 shows the analytical results obtained by our proposed algorithm and simulation results. First, \( E[R] \) is proportional to \( T_{\text{max}} \). When \( T_{\text{max}} \) reaches certain value, \( E[R] \) stops increasing. With each value of \( T_{\text{min}} \), there are three different regions for optimal values of \( T_{\text{max}} \) with different constraint of average frame response delay: no solution, unique solution and many solutions. Besides the explanations in 2.2 for each region, we can also interpret these phenomena as followed.

- No solution: occurs when the required \( E[R] \) is too small. This means that with fixed \( T_{\text{min}} \), \( E[R] \) must be greater than the given value.
- One solution: occurs when the required \( E[R] \) lies in \([E[R]_{\text{min}}, E[R]_{\text{max}})\). When \( T_{\text{max}} \) increases, the duration for a sleep cycle increases; therefore, MAC frames arriving in MSSs’ sleep interval need to wait for a longer time. This increases average frame response delay.
- Many solutions: occurs when the \( E[R] \) is equal or greater than \( E[R]_{\text{max}} \). In Fig. 3, when \( T_{\text{max}} \) reaches certain value, \( E[R] \) stops increasing because the probabilities of MAC frames arriving only in the sleep cycles whose final sleep intervals equal to \( T_{\text{max}} \) is almost zero.

As illustrated in Fig. 3, the simulation results match the analytical results pretty well. Assume that we have to find the optimal \( T_{\text{max}} \) with \((E[R], T_{\text{min}}, \lambda, L)\) as \((1.074,1,1,1)\);
then, the possible values of $T_{\text{max}}$ are 1, 2 and 4. We choose $E[R]$ as 1.074, one of the values which give three possible $T_{\text{max}}$’s, to clear how our proposed algorithm improves energy consumption of a MSS in sleep mode. Either by using our algorithm or using simulation, the optimal $T_{\text{max}}$ is 4. Figure 4 shows the relationship between $T_{\text{max}}$ and the energy consumption of a MSS. The figure also shows the optimal energy consumption when $E[R]$ equals 1.074. There are three cases of possible energy consumptions with $T_{\text{max}}$ is 1, 2 or 4. In Fig. 4, we observe that $T_{\text{max}}$’s being equal to 4 gives lower energy consumption than $T_{\text{max}}$’s being equal to 1 or 2. In other words, our algorithm minimizes energy consumption.

4. Conclusion

Besides energy consumption, frame response delay is another important performance metric in 802.16e. Given the constraint of frame response delay, we proposed an analytical model and its corresponding algorithm to quickly determine the optimal value of final sleep interval. This work has never been done before. The evaluations by both analytical results and simulation results show that the value of the final sleep interval obtained by our algorithm guarantees to minimize energy consumption with respect to a frame response delay constraint. Therefore, the methodology and the analysis in this letter provide useful guidance to energy saving.

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