An Efficient Sleep Mode Management Scheme in IEEE 802.16e Networks

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***Abstract* – In IEEE 802.16e networks, the mobility of mobile stations (MSs) induces that energy saving becomes an important issue for the battery-powered MSs to extend their operational lifetime. Based on the characteristics of Power Saving Class (PSC) types and data delivery service types defined in IEEE 802.16e standard, we propose an efficient sleep mode management scheme to save energy. Using the quality of service (QoS) parameters associated with transport connections, we not only design the downlink and uplink PSC parameters, but also introduce the PSC anti-expansion mechanism. The analyses and simulation results demonstrate that the proposed scheme can minimize the energy consumption of MSs under the condition that the QoS requirements of each connection are guaranteed.**

***Keyword* - sleep mode, PSC, energy management, 802.16e, QoS.**

I. INTRODUCTION

The latest IEEE 802.16e standard [1] supports the mobility of mobile station (MS), which makes energy saving a significant challenge. Through sleep mode operation [1][3-10], the energy consumption of battery-powered MS is decreased; the lifetime of MS is extended before re-charging.

The 802.16e standard defined Power Saving Class (PSC) types and the sleep mode operation is just on a PSC basis. *Unavailability interval* [1] is the intersection of sleep windows of all active PSCs in downlink (DL, i.e., BS-to-MS) or uplink (UL, i.e., MS-to-BS) direction at MS. During unavailability interval, several physical components of MS can be turned off, resulting in less energy consumption. If PSCs are not managed efficiently, the number of PSCs is large when many connections with different demands exist. Thus, unavailability interval appears difficultly and energy saving becomes impossible. However, to efficiently manage PSCs in achieving the minimum energy consumption is not discussed in the standard at all. The research works [6-10] on sleep mode in 802.16e network were just focused on the performance analysis. [6-8] only considered DL traffic in sleep mode operation, whereas [9-10] took both DL and UL traffics into account. But all of them regarded the MS as a whole without differentiating PSCs and these performance analysis models were not suitable for PSC-based sleep mode operation. Therefore, the research efforts on this issue are urgently needed.

In this paper, an efficient sleep mode management scheme and the corresponding performance analysis model are proposed for PSC-based sleep mode operation. On the one hand, with guaranteed data transfer, the parameters of DL/UL PSCs are designed to maximize the sleep windows. On the other hand, under the condition that the QoS requirements of connections are satisfied, the PSC anti-expansion mechanism is introduced to minimize the number of PSCs and increase the possibility of sleep windows overlap.

The rest of this paper is organized as follows. Section II briefs the background knowledge. In Section III, our sleep mode management scheme is proposed. Section IV designs the performance analysis model for the proposed scheme. Simulation results are presented in Section V. Finally, conclusions are made.

II. BACKGROUND KNOWLEDGE

A. *Data Delivery Services*

In IEEE 802.16e standard, five types of data delivery services were defined [1]: unsolicited grant service (UGS), real-time variable rate (RT-VR) service, extended real-time variable rate (ERT-VR) service, non-real-time variable rate (NRT-VR) service and best effort (BE) service. The first three types support real-time applications; the others carry non-real-time applications.

- UGS is provided by the BS with periodic fixed-size grants via scheduling;
- For UL RT-VR connection, the BS provides periodic bandwidth request (BR) opportunities via unicast polling;
- When the BR size of ERT-VR connection is non-zero, ERT-VR is handled as UGS, otherwise as RT-VR. So, ERT-VR is not specifically differentiated in our design.

B. *Sleep Mode in IEEE 802.16e Standard*

In sleep mode, a group of connections that have common demand properties is defined as a *PSC*. The BS associates each subordinate MS involved in sleep mode operation with one or several PSCs. *Activation* of PSC means beginning alternate sleep/listening windows of this class; *deactivation* of PSC means starting the normal operation of the corresponding connections. Three types of PSCs were defined in [1]:

1) PSC of type I

This PSC type is applied to NRT-VR and BE connections. *Initial-sleep window* is for the first sleep interval and each next sleep window is twice the size of the previous one, but not greater than *final-sleep window*. Sleep windows are interleaved with constant-size *listening windows*. Sending and receiving data at connections, which belong to type I PSC, are not expected during listening windows.

2) PSC of type II

This PSC type is suitable for UGS, RT-VR and ERT-VR connections. All sleep windows are of the same size as *initial-sleep window*. Sleep windows are interleaved with fixed-duration *listening windows*. As opposite to type I PSC, sending and receiving data at connections, which compose the

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type II PSC, are allowed during listening windows.

3) PSC of type III

This PSC type is used for management connections. It has no listening window and only involves a single sleep window specified by *final-sleep window* parameter. Deactivation of PSC occurs automatically after expiration of sleep window.

III. Proposed Sleep Mode Management Scheme

The 802.16 MAC is connection-oriented [1-2]. *Connection* is a unidirectional mapping between BS and MS MAC peers. There are two kinds of connections: management connection and transport connection. The former is used to transport management messages; the latter is for user data. When the traffic of a DL transport connection appears on the BS during the sleep window of corresponding PSC, the MS may be informed by the BS of terminating the PSC's active state in the next listening window if necessary. In contrast, when the UL traffic demand on a transport connection appears during its sleep window, MS may deactivate the PSC immediately if necessary. Due to the different deactivation mechanisms, differentiating UL and DL transport connections in sleep mode operation is reasonable and necessary.

Service flows (SFs), which are unidirectional flows of MAC service data units (SDUs), provide a mechanism for QoS management. Each SF is characterized by a set of QoS parameters such as maximum sustained traffic rate, maximum latency, unsolicited grant/polling interval, etc. To transport data, SFs are one-to-one mapped to connections. Thus, each transport connection is also associated with a set of QoS parameters.

A. Basic Parameter Definition

We define a sleep window and its subsequent listening window as a *sleep cycle* for types I and II PSC. Sleep and listening windows are measured in the units of MAC frame duration, *T*. Notations $dr \in \{U$ (uplink), D (downlink), B (both uplink and downlink)$\}$ and $tp \in \{N$ (NRT-VR/BE), U (UGS), R (RT-VR), M (management connection)$\}$. Let $SW_{j,i}^{dr,tp}$ and $LW_{j}^{dr,tp}$ denote the sizes of the *i*th sleep window and listening window associated with the *j*th PSC, which is composed of the *tp*-type connections in *dr*-direction, respectively. Thus, $SW_{j,1}^{dr,tp}$ and $SW_{j,F}^{dr,tp}$ stand for the corresponding initial and final sleep windows. It is noted that the definitions of parameters with superscripts *dr*, *tp* and subscripts *j*, *i* in the subsequent text follow the explanation mentioned above. $SW_{\min}$ and $SW_{\max}$ are the minimum and maximum sleep windows specified by the system.

B. Proposed Sleep Mode Management Scheme

Energy consumption of MS is really reduced in the unavailability interval. The more the sleep windows of all PSCs overlap, the longer the unavailability intervals are and the more the energies are saved for the MS. To maximize the unavailability interval along with guaranteed data transfer, sleep windows should be as long as possible and the number of PSCs should be as few as possible.

1) For PSC of type I

Carrying delay insensitive applications, NRT-VR/BE connections may be marked as belonging to one PSC in UL and DL directions, respectively. In DL direction (referring to Fig. 1 (a)), the related PSC parameters are set as follows:

$$\begin{cases} SW_{1,1}^{D,N} = \max\left(SW_{\min}, \left\lceil \dfrac{\mu_1^{D,N} - \sigma_1^{D,N}}{T} \right\rceil\right), \\ SW_{1,F}^{D,N} = \min\left(SW_{\max}, \left\lceil \dfrac{\mu_1^{D,N} + \sigma_1^{D,N}}{T} \right\rceil\right), \quad F \geq 2 \\ SW_{1,i}^{D,N} = \min(2^{i-1} SW_{1,1}^{D,N}, SW_{1,F}^{D,N}), \quad i = 1, 2, 3, \cdots \\ LW_1^{D,N} = 1, \end{cases} \tag{1}$$

where $\mu_1^{D,N}$ and $\sigma_1^{D,N}$ are the mean and standard deviation of non-real-time traffic arrival interval, which can be obtained through simulation or practical measure. During listening window $LW_1^{D,N}$, MS listens to the traffic indication (MOB_TRF-IND) message broadcasting from BS and decides whether to continue the active state of the PSC (negative indication in MOB_TRF-IND) or terminate it (positive indication in MOB_TRF-IND).

As for the UL PSC (seeing Fig. 1 (b)), set parameters as (2).

$$\begin{cases} SW_{1,1}^{U,N} = SW_{1,F}^{U,N} = SW_{\max}, \\ SW_{1,i}^{U,N} = \min(2^{i-1} SW_{1,1}^{U,N}, SW_{1,F}^{U,N}) = SW_{\max}, \quad i = 1, 2, 3, \cdots \\ LW_1^{U,N} = 0. \end{cases} \tag{2}$$

Once the PSC is activated, it always stays in the sleep windows until the UL traffic on these connections arrives at the MS. With that, the MS deactivates the PSC immediately and corresponding connection sends BR message for the UL traffic.

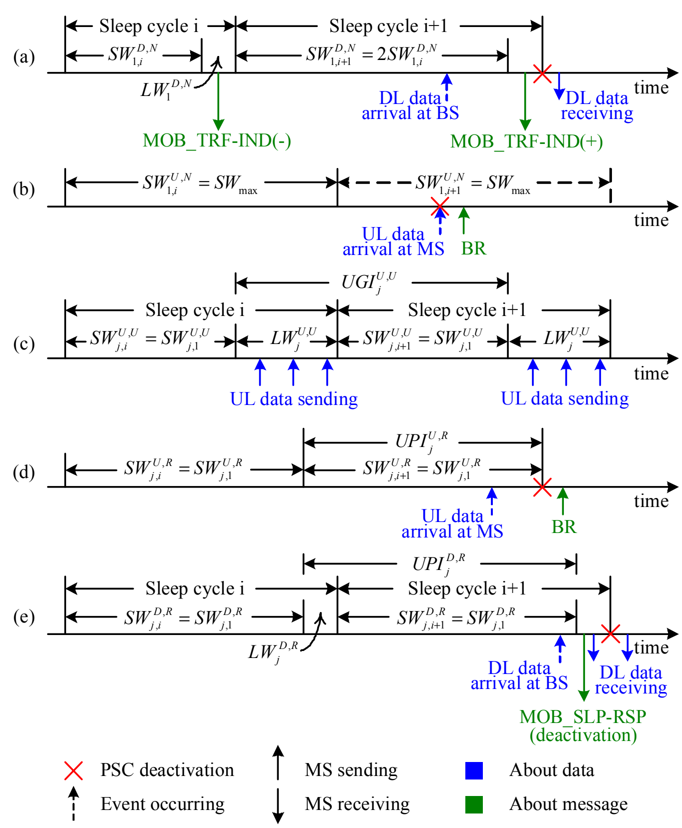

Fig. 1. Schematic representation of sleep mode operation.

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2) For PSC of type II

Unsolicited grant interval for UGS/ERT-VR connection and unsolicited polling interval for RT-VR connection are integral numbers of MAC frames. Define $UGI_j^{dr,U} / UPI_j^{dr,R}$ as the unsolicited grant/polling interval parameter of the *j*th PSC.

a) Establish a new PSC based on a UGS connection

For UL UGS connection *x*, the listening window LW_x is

$$LW_x = \left\lceil \frac{s_x \times \lambda_x \times UGI_x \times T}{r_x \times g_x} \right\rceil, \tag{3}$$

where s_x, λ_x, UGI_x, r_x and g_x denote the size of fixed-length packet (bits/packet), packet arrival rate (packets/second), unsolicited grant interval (frame), maximum sustained traffic rate (bits/second) and the granted transmission interval (second) per UL subframe for connection *x*, respectively. Under the condition of $UGI_x - LW_x \geq SW_{\min}$, the windows for the *j*th PSC, which is determined by connection *x*, should be set as

$$\begin{cases} LW_j^{U,U} = LW_x, \\ SW_{j,i}^{U,U} = UGI_x - LW_x, \quad i = 1, 2, 3, \cdots \\ UGI_j^{U,U} = UGI_x. \end{cases} \tag{4}$$

In such case, which is illustrated in Fig. 1 (c), connection *x* is always in the sleep mode, alternate sleep window and listening window, still guaranteeing the normal transmission.

Same method is applied to DL UGS connections. But, due to the propagation and processing delay, each sleep cycle has a time offset relative to that of the corresponding UL connection.

b) Establish a new PSC based on a RT-VR connection

Suppose UL RT-VR connection *x* has unsolicited polling interval UPI_x. Only when each UPI_x elapses, is connection *x* granted the transmission opportunity for BR. If the *j*th PSC's parameters are designed according to connection *x*, then

$$\begin{cases} LW_j^{U,R} = 0, \\ SW_{j,i}^{U,R} = UPI_x, \quad i = 1, 2, 3, \cdots \\ UPI_j^{U,R} = UPI_x. \end{cases} \tag{5}$$

When UL traffic needs to be sent, the PSC will be deactivated at the end of the current sleep window (seeing Fig. 1 (d)).

If connection *x* is a DL RT-VR connection, assume that connection *x'* mapping from the sending MS to the sending BS is the corresponding UL connection of *x*. Fig. 2 sketches this situation. Let UPI'_x denote the unsolicited polling interval of *x'*. By information forwarding in backbone network, the receiving BS gets the parameter UPI'_x and sets $UPI_x = UPI'_x$. Only when polling is done at the sending MS, may connection *x'* possibly make BR and may data on connection *x'* be sent at the subsequent allocation. Accordingly, after a certain delay, data arrival at the receiving BS may be possible. Here, the delay results from bandwidth request/grant of connection *x'*, processing at middle nodes as well as data propagation, which are produced in the process shown by the red lines in Fig. 2 schematically, and the value of this delay is obtained from the data transfer before the sleep mode operation. Provided that $UPI_x - 1 \geq SW_{\min}$ is satisfied, set the parameters of the *j*th PSC as

$$\begin{cases} LW_j^{D,R} = 1, \\ SW_{j,i}^{D,R} = UPI_x - 1, \quad i = 1, 2, 3, \cdots \\ UPI_j^{D,R} = UPI_x. \end{cases} \tag{6}$$

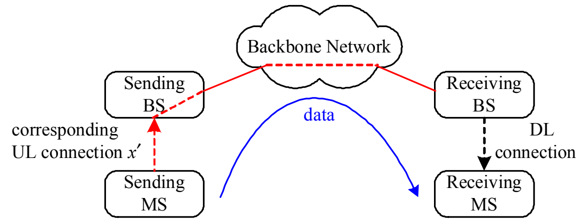

Fig. 2. Explanation for the design of PSC composed of DL RT-VR connections.

When the data addressing to connection *x* arrives at the receiving BS, the BS sends unsolicited sleep response (MOB_SLP-RSP) message indicating the PSC deactivation and starts to forward the data in DL subframe during the immediate listening window. The receiving MS picks up the data in the current DL subframe for connection *x* and deactivates the corresponding PSC at the end of the listening window for subsequent data receiving (referring to Fig. 1 (e)).

c) PSC anti-expansion mechanism

In order to minimize the number of PSCs, each connection should attempt to be associated with an existing PSC, which is called as "*PSC anti-expansion*". Based on the direction and the data delivery service type of connection, the existing kindred PSCs are checked whether the PSC parameters meet the QoS requirements of the connection or not. If the QoS requirements are satisfied, the connection will be associated with the PSC and begin the sleep mode operation at the PSC's immediate sleep window; otherwise, a new PSC will be established based on this connection using the method mentioned above. Because the sleep mode operation just affects the packet delay, only the delay property is considered.

Fig. 3 shows the PSC anti-expansion mechanism. $\mathrm{J}^{\mathrm{dr,tp}}$ is the number of the existing PSCs that are composed of the *tp*-type connections in *dr*-direction; $\mathrm{UGI}^{\mathrm{dr,tp}}/\mathrm{UPI}^{\mathrm{dr,tp}}$ is the parameter array, which consists of the unsolicited grant/polling intervals of the corresponding PSCs. The five judgment conditions, referring to Fig. 4, are stated as follows.

Condition 1: for UL/DL UGS connection, if $t_{j,S,i} - T \leq t_{x,A,i} < t_{j,L,i}$, then (7) is met;

$$\begin{cases} t_{j,L,i} - t_{x,A,i} + t_g \leq L_{\max}, \\ LW_x \leq LW_j^{U,U} \text{ for UL, (or } LW_x \leq LW_j^{D,U} \text{ for DL).} \end{cases} \tag{7}$$

Condition 2: for UL/DL UGS connection, if $t_{j,L,i} \leq t_{x,A,i} < t_{j,S,i+1} - T$, then (8) is met;

$$\begin{cases} res(\dfrac{t_{j,S,i+1} - t_{x,A,i}}{T}) + t_g \leq L_{\max}, \\ LW_x \leq \left\lfloor \dfrac{t_{j,S,i+1} - t_{x,A,i}}{T} \right\rfloor, \end{cases} \tag{8}$$

where *res*( ) denotes the residue of the division in the bracket.

Condition 3: for DL RT-VR connection, if $t_{j,S,i} \leq t_{x,A,i} < t_{j,L,i}$, then (9) is met;

$$t_{j,L,i} - t_{x,A,i} + t_g \leq L_{\max}. \tag{9}$$

Condition 4: for DL RT-VR connection, if $t_{j,L,i} \le t_{x,A,i} < t_{j,S,i+1}$, then (10) is met;

$$t_{j,L,i+1} - t_{x,A,i} + t_g \le L_{\max} . \qquad (10)$$

Condition 5: for UL RT-VR connection, if $t_{j,S,i} \le t_{x,A,i} < t_{j,S,i+1}$, then (11) is met.

$$t_{j,S,i+1} - t_{x,A,i} + t_{BR} + t_g \le L_{\max} . \qquad (11)$$

Here, $t_{x,A,i}$ is the instant at which the traffic on connection x arrives at BS in DL direction (or at MS in UL direction) in the ith sleep cycle of the jth checked PSC; L_{max} denotes the maximum tolerable latency between the ingress of a packet to the Convergence Sublayer and the forwarding of the SDU to BS or MS air interface; t_g is the time offset of bandwidth grant relative to the start time of current MAC frame and t_{BR} represents the time for bandwidth requesting.

3) For PSC of type III

Since the management message exchange requires UL/DL management connections to be in wake state simultaneously, all management connections compose a single PSC without differentiating UL and DL. The single sleep window is

$$SW_{1,F}^{B,M} = t_w - t_s , \qquad (12)$$

where t_s is the beginning time when all PSCs of types I and II are in their sleep windows and no management operation is required; t_w is the beginning time when either of the following situations happens: (a) any PSC of types I and II either enters its listening window or is deactivated, or (b) any management operation is demanded.

```
PSCAntiExpansion( )
{
  switch (the direction and type of connection x)
  {
    case "DL_UGS":
      PSCCheck(J^{D,U}, UGI_x, UGI^{D,U}, condition_1, condition_2); break;
    case "UL_UGS":
      PSCCheck(J^{U,U}, UGI_x, UGI^{U,U}, condition_1, condition_2); break;
    case "DL_RT-VR":
      PSCCheck(J^{D,R}, UPI_x, UPI^{D,R}, condition_3, condition_4); break;
    case "UL_RT-VR":
      PSCCheck(J^{U,R}, UPI_x, UPI^{U,R}, condition_5, 0); break;
    case "DL_ERT-VR":
      if (BR_x!=0)      // BR_x is the BR size of the ERT-VR connection.
        PSCCheck(J^{D,U}, UGI_x, UGI^{D,U}, condition_1, condition_2);
      else PSCCheck(J^{D,R}, UGI_x, UPI^{D,R}, condition_3, condition_4); break;
    case "UL_ERT-VR":
      if (BR_x!=0) PSCCheck(J^{U,U}, UGI_x, UGI^{U,U}, condition_1, condition_2);
      else PSCCheck(J^{U,R}, UGI_x, UPI^{U,R}, condition_5, 0);
  }
}
PSCCheck(int N, int par_x, int par_array[ ], int con_a, int con_b)
// N is the number of the checked PSCs;
// par_x is the compared parameter of connection x;
// par_array[ ] is the parameter array of the kindred PSCs;
// con_a and con_b represent the checked judgment conditions.
{
  for (j=1; j<=N; j++)
  {
    if ((par_x == par_array[j])&& (con_a or con_b is satisfied))
    {
      connection x is associated with the jth kindred PSC; break;
    }
  }
  if (j > N)    establish a new PSC based on connection x;
}
```

Fig. 3. PSC anti-expansion mechanism.

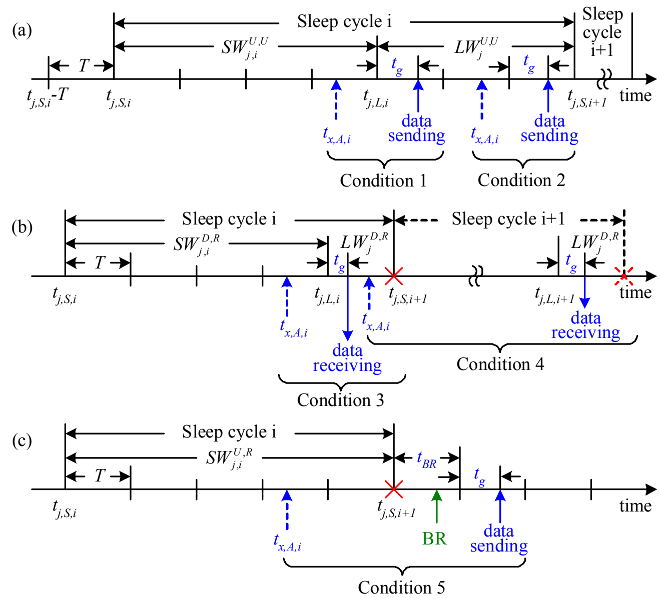

Fig. 4. Judgment conditions in the PSC anti-expansion.

IV. Performance Analysis

Assume that the traffic arrival on the *tp*-type connections in *dr*-direction, which compose the *j*th kindred PSC, follows Poisson process with arrival rate $\lambda_j^{dr,tp}$. This assumption may oversimplify the analysis of sleep mode, but a loose upper bound of performance may be obtained before introducing the correlated arrival processes [8]. Active state of PSC includes a series of *sleep cycle states* and PSC being in its sleep window is termed as *sleep state*. In PSC's inactive state, if no traffic is sent or received on the corresponding connections for an idle period $I_j^{dr,tp}$, the PSC will be activated. $I_j^{dr,tp}$ is also an integral number of MAC frames.

As to the PSCs composed of DL NRT-VR/BE, DL RT-VR and UL RT-VR connections, continuous-time Markov chain models [8] can be used to analyze their state probabilities. Let $C_{j,0}^{dr,tp}$ and $C_{j,i}^{dr,tp}$ (i>0) stand for the jth PSC being in the inactive state and the ith sleep cycle state, respectively. $Pc_{j,0}^{dr,tp}$, $Pc_{j,i}^{dr,tp}$ and $Ps_{j,i}^{dr,tp}$ (i>0) denote the steady state probabilities of the jth PSC staying at the inactive state, the ith sleep cycle state and the ith sleep state, respectively. $Ps_j^{dr,tp}$ represents the probability of the jth PSC being in all the sleep states. The transition probabilities from $C_{j,0}^{dr,tp}$ to $C_{j,1}^{dr,tp}$ and from $C_{j,i}^{dr,tp}$ to $C_{j,i+1}^{dr,tp}$ are denoted by $\alpha_{j,0}^{dr,tp}$ and $\alpha_{j,i}^{dr,tp}$, which are the probabilities of no traffic arriving during their respective intervals, $I_j^{dr,tp}$ and $SW_{j,i}^{dr,tp} + LW_j^{dr,tp}$.

$$\alpha_{j,0}^{dr,tp} = e^{-\lambda_j^{dr,tp} \times I_j^{dr,tp} \times T} , \qquad (13)$$

$$\alpha_{j,i}^{dr,tp} = e^{-\lambda_j^{dr,tp} \times (SW_{j,i}^{dr,tp} + LW_j^{dr,tp}) \times T} , \quad i > 0 \qquad (14)$$

A. Probabilities of Type I PSCs in Sleep State

Based on Fig. 5 (a), the steady state equation of DL type I

PSC is obtained as

$$\begin{cases} \mathbf{Pc} = \mathbf{Pc} \bullet \mathbf{Pt}, \\ \sum_{i=0}^{F} Pc_{1,i}^{D,N} = 1, \quad F \geq 1 \end{cases} \tag{15}$$

where

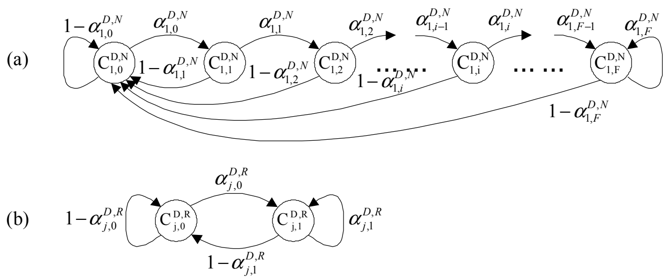

Fig. 5. State transition diagrams for PSCs composed of (a) DL NRT-VR/BE and (b) DL RT-VR connections.

$$\mathbf{Pc} = \left[Pc_{1,0}^{D,N} \quad Pc_{1,1}^{D,N} \quad Pc_{1,2}^{D,N} \quad \cdots \quad Pc_{1,i}^{D,N} \quad \cdots \quad Pc_{1,F}^{D,N} \right],$$

$$\mathbf{Pt} = \begin{bmatrix} 1-\alpha_{1,0}^{D,N} & \alpha_{1,0}^{D,N} & 0 & 0 & \cdots & 0 \\ 1-\alpha_{1,1}^{D,N} & 0 & \alpha_{1,1}^{D,N} & 0 & \cdots & 0 \\ 1-\alpha_{1,2}^{D,N} & 0 & 0 & \alpha_{1,2}^{D,N} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1-\alpha_{1,F-1}^{D,N} & 0 & 0 & 0 & \cdots & \alpha_{1,F-1}^{D,N} \\ 1-\alpha_{1,F}^{D,N} & 0 & 0 & 0 & \cdots & \alpha_{1,F}^{D,N} \end{bmatrix}.$$

The probabilities $Pc_{1,0}^{D,N}$, $Pc_{1,i}^{D,N}$ and $Pc_{1,F}^{D,N}$ are solved as

$$\begin{cases} Pc_{1,0}^{D,N} = \dfrac{1-\alpha_{1,F}^{D,N}}{(1-\alpha_{1,F}^{D,N}) \times (1 + \sum_{i=0}^{F-2} \prod_{k=0}^{i} \alpha_{1,k}^{D,N}) + \prod_{k=0}^{F-1} \alpha_{1,k}^{D,N}}, \\ Pc_{1,i}^{D,N} = Pc_{1,0}^{D,N} \prod_{k=0}^{i-1} \alpha_{1,k}^{D,N}, \quad 1 \leq i \leq F-1 \ \ if \ \ F \geq 2 \\ Pc_{1,F}^{D,N} = \dfrac{Pc_{1,0}^{D,N}}{1-\alpha_{1,F}^{D,N}} \prod_{k=0}^{F-1} \alpha_{1,k}^{D,N}. \end{cases} \tag{16}$$

Thus, the probabilities of the PSC staying at the *i*th sleep state and all the sleep states are

$$Ps_{1,i}^{D,N} = \frac{SW_{1,i}^{D,N}}{SW_{1,i}^{D,N} + LW_{1}^{D,N}} Pc_{1,i}^{D,N}, \quad 1 \leq i \leq F \tag{17}$$

$$Ps_{1}^{D,N} = \sum_{i=1}^{F} Ps_{1,i}^{D,N}. \tag{18}$$

In terms of the UL direction, the PSC can be deactivated at discretion, regardless of the end of sleep window. The sleep state probability can be approximated as (19).

$$Ps_{1}^{U,N} = \frac{\mu_{1}^{U,N} - \gamma_{1}^{U,N} - I_{1}^{U,N} \times T}{\mu_{1}^{U,N}} = \frac{1/\lambda_{1}^{U,N} - \gamma_{1}^{U,N} - I_{1}^{U,N} \times T}{1/\lambda_{1}^{U,N}}, \tag{19}$$

where $\mu_{1}^{U,N}$ and $\gamma_{1}^{U,N}$ are the mean interval of traffic arrival and the mean duration of traffic burst transmission, respectively. Under the assumption of Poisson arrival process with rate $\lambda_{1}^{U,N}$, $\mu_{1}^{U,N} = 1/\lambda_{1}^{U,N}$.

B. *Probabilities of Type II PSCs in Sleep State*

1) For PSC composed of UGS connections

As for this kind of PSC, its constant-size sleep window and constant-size listening window alternate periodically without inactive state. Therefore, the sleep state probability of this kind of PSC is expressed by (20).

$$Ps_{j}^{dr,U} = \frac{SW_{j,1}^{dr,U}}{SW_{j,1}^{dr,U} + LW_{j}^{dr,U}}, \quad dr \in \{U,\ D\} \tag{20}$$

2) For PSC composed of RT-VR connections

As observed in Fig. 5, (b) is the particular case of (a). Substitute *F=1* into (16) and replace the superscript *N* and the subscript *1* with *R* and *j*, respectively. Then,

$$Pc_{j,1}^{D,R} = \frac{\alpha_{j,0}^{D,R}}{1+\alpha_{j,0}^{D,R} - \alpha_{j,1}^{D,R}}. \tag{21}$$

$$Ps_{j}^{D,R} = \frac{SW_{j,1}^{D,R}}{SW_{j,1}^{D,R} + LW_{j}^{D,R}} Pc_{j,1}^{D,R}. \tag{22}$$

The solution for this kind of PSC in UL direction is similar to the DL case except for $LW_{j}^{U,R} = 0$. So,

$$Ps_{j}^{U,R} = Pc_{j,1}^{U,R} = \frac{\alpha_{j,0}^{U,R}}{1+\alpha_{j,0}^{U,R} - \alpha_{j,1}^{U,R}}. \tag{23}$$

C. *Saved Energy*

Energy saving really occurs during unavailability intervals, i.e., all the DL or UL PSCs stay at their sleep states simultaneously. Compared with data transmission, management message exchange spends much less time. For the sake of simplicity, the time used for management message exchanges, which are performed in the intersections of all types I and II PSCs' sleep windows, is ignored. Thus, only types I and II PSCs need to be considered. Because PSCs being in their sleep states are mutually independent, based on the multiplication theorem of probabilities for independent events, the average saved energy per time unit in *dr*-direction, E_{s}^{dr}, is obtained as (24). Here, $dr \in \{U, D\}$.

$$E_{s}^{dr} = Ps_{1}^{dr,N} \times \prod_{j=1}^{J^{dr,U}} Ps_{j}^{dr,U} \times \prod_{j=1}^{J^{dr,R}} Ps_{j}^{dr,R} \times (E_{n}^{dr} - E_{u}^{dr}), \tag{24}$$

where E_{n}^{dr} and E_{u}^{dr} denote the average consumed energies per time unit in the normal operation interval and the unavailability interval in *dr*-direction.

V. SIMULATION RESULTS

To evaluate the performance of the proposed scheme, we design a simulation model with OPNET Modeler. In the simulation, we use the following parameters: T=5ms, $SW_{\min}$=2 (in the unit of frame duration, T, i.e., 10ms), $SW_{\max}$=32 (i.e., 160ms), $I_{1}^{U,N} = I_{1}^{D,N}$=3 (i.e., 15ms). For the PSCs composed of RT-VR connections, $I_{j}^{dr,R}$=2 $UPI_{j}^{dr,R}$. In terms of the energy consumption units, E_{n}^{D}=10, E_{n}^{U}=15 and $E_{u}^{D} = E_{u}^{U}$=1.

Fig. 6 shows the UL and DL average packet delays versus the average packet arrival rate λ in normal operation and in sleep mode operation with proposed scheme. In Fig. 6 (a), the lines of these two cases for UL NRT-VR/BE connections are similar. Since the UL type I PSC is deactivated as soon as the packets on these connections arrive, sleep mode operation has no effect on packet delay. The delay mainly results from the contention of BR opportunity and bandwidth grant. On the contrary, sleep mode operation affects the delay of DL NRT-VR/BE connections greatly, especially when λ is small, shown in Fig. 6 (b). It can be explained that the DL type I PSC is only deactivated at the end of sleep windows. Smaller λ means the PSC stays in active state for more time and sleep window increasing exponentially results in larger delay.

As observed from Fig. 6, compared with the normal operation, the sleep mode operation with the proposed scheme induces more delay for the UGS/RT-VR connections, but the delay requirements of these connections can still be guaranteed. Satisfying the delay requirements of connections, the PSC anti-expansion mechanism associates the connections, which have different traffic arrival instants in each grant/polling period, with one PSC, and the data transmission may be deferred till the end of the current sleep window. As λ increases, activating PSC becomes infrequent and the ranges of PSC anti-expansion are decreased, which make the effect of the sleep mode on delay unobvious and the delay properties of these two cases tend to be consistent.

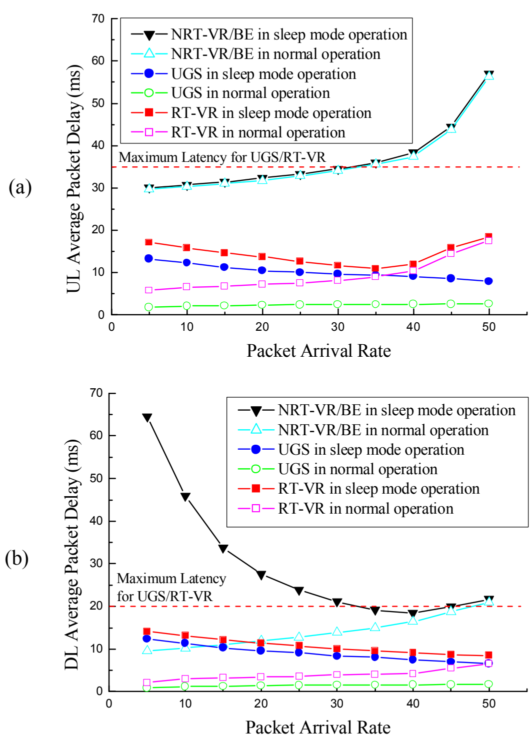

Fig. 6. Average Packet Delay.

Fig. 7 reveals the average energy consumption of MS in normal operation and in sleep mode operations with/without PSC anti-expansion mechanism. In sleep mode operation with PSC anti-expansion, less PSCs are set and longer unavailability intervals are obtained, which result in MS consuming less energy. The figure also illustrates that the analyses and simulation results for the proposed scheme are matched pretty well.

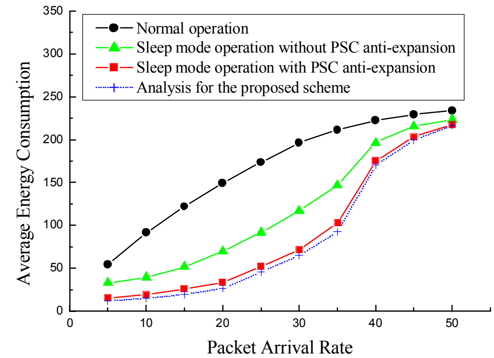

Fig. 7. Average Energy Consumption.

VI. CONCLUSION

In IEEE 802.16e standard, sleep mode was defined, which aims at decreasing the energy consumption to extend the lifetime of MS. But how to manage the sleep mode operation efficiently was not specified in it. In this paper, based on the characteristics of PSC types and the properties of data delivery service types, an efficient sleep mode management scheme is proposed. With guaranteed data transfer, the design of PSC parameters to maximize sleep windows and the usage of PSC anti-expansion mechanism to decrease the number of PSCs facilitate the lengthening of unavailability intervals. Accordingly, the energy of MS is saved greatly. The analyses and simulation results show that the proposed scheme can minimize the energy consumption of MS under the condition that the QoS requirements of connections are satisfied.

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