A Statistical Power-Saving Mechanism for IEEE 802.16 Networks

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***Abstract*—The power-saving class of type I (PSC I), one of the sleep mode operations in the IEEE 802.16e standard, is designed to reduce power consumption for non-real-time traffic. However, the inefficiency of PSC I comes from its configuration and operation. Based on the notions of IEEE 802.16m sleep mode operation, a statistical sleep window control (SSWC) approach is proposed to improve energy efficiency for mobile stations in this paper. The SSWC approach exploits a partially observable Markov decision process (POMDP) to conjecture the present traffic state. Based on the properties of POMDP, the optimal policy for sleep window selection is acquired in the SSWC approach. The performance evaluation is conducted and compared via the simulations. Simulation results show that the proposed SSWC approach outperforms the IEEE 802.16e PSC I scheme and the inferred IEEE 802.16m power-saving mechanism.**

I. INTRODUCTION

The IEEE 802.16-2004 standard [1] for broadband wireless networks (BWNs) is developed to support various demand for high capacity, high data rate, and advanced multimedia services. The IEEE 802.16e amendment [2] enhances the original standard by addressing mobility and power-saving issues for mobile stations (MSs). In the IEEE 802.16e standard, sleep mode is defined as a state that both minimizes the power consumption of MS and decreases the usage of interface resources within serving base station (BS). In the sleep mode, the MS is provided with a series of alternate sleep windows and listening windows. The sleep window is a time period in which the BS shall not transmit data or management messages to the MS. During the listening window, on the other hand, the MS is expected to transmit/receive data or management messages based on the same manner as in the state of normal operation. Three types of sleep mode operation, which correspond to power-saving classes (PSCs), are specified in the standard for supporting different types of traffic, i.e., type I for non-real-time traffic, type II for real-time traffic, and type III for multicast and management traffic.

Fig. 1 illustrates the operation of PSC of type I (PSC I) in IEEE 802.16e system. The MS enters sleep mode while it has been idle for a period without data transportation in normal mode. Three major parameters, including length of initial-sleep window (T_{min}), length of final-sleep window (T_{max}), and length of listening window, are defined for PSC I operation. As shown in Fig. 1, the PSC I starts with a sleep window of length $T_{SW_1} = T_{min}$. After the sleep window, a fixed-length listening window is provided for the MS to receive traffic indication message MOB-TRF-IND, which is broadcasted from the BS. This message indicates whether there has been traffic addressed to the MS. If the MOB-TRF-IND indicates in the negative, the MS continues in the sleep mode after the listening window; otherwise it will return to the normal mode for data reception. In the case that the MS continues in the sleep mode, the length of the next sleep window is double of the previous one, e.g., $T_{SW_2} = 2 \times T_{SW_1}$. This process is repeated as long as the length of sleep window does not exceed T_{max}. When the length of sleep window reaches T_{max}, the length of subsequent sleep windows will remain constant at T_{max}. On the other hand, in the case that the sleep mode of the MS is reactivated in the normal mode, the length of the first sleep window is reset as T_{min}, e.g., $T_{SW_4} = T_{min}$ in Fig. 1

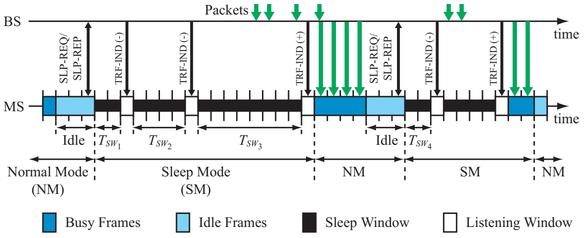

Fig. 1. Schematic diagram of PSC I in IEEE 802.16e system.

The performance modeling and analysis of PSC I have been investigated in resent research studies. The work in [3] analytical modeled the basic operation specified in the IEEE 802.16e standard; while the queuing behavior that modeled as $M/GI/1/N$ queue with multiple vacations is discussed in [4]. The complex model for multiple downlink and uplink traffic is considered and modeled in [5]. From the analytical results of these literatures, it can be perceived that the inefficiency of PSC I comes from two parts: (i) the idle period before each sleep mode and (ii) a large number of under-utilized listening windows that only be utilized to receive traffic indication messages in the sleep mode (as shown in Fig. 1).

In order to improve the energy efficiency and to provide a flexible sleep mode operation for IEEE 802.16m system, a statistical sleep window control (SSWC) approach is proposed in

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this paper. It is noted that the IEEE 802.16m system, evolved from the IEEE 802.16e system, is developed for supporting advanced services in the future; while the relevant standard is designed by IEEE 802.16m task group [6]. The proposed SSWC approach determines the length of each sleep window appropriate for present traffic state and delay constraint. While the state of non-real-time traffic is difficult to be obtained, the number of buffered packets can provide hits to estimate the current traffic state. Thus the SSWC approach exploits a partially observable Markov decision process (POMDP) [7] to conjecture the present traffic state. Based on the properties of POMDP, the optimal policy for sleep window selection is acquired in the SSWC approach. The performance evaluation is conducted and compared via the simulations. Simulation results show that the proposed SSWC approach outperforms the IEEE 802.16e PSC I scheme and the inferred IEEE 802.16m power-saving mechanism.

The rest of the paper is organized as follows. Section II briefly describes the requirements for sleep mode operation in IEEE 802.16m system and formulates the target problem. The proposed SSWC approach is explained in Section III; while the performance evaluation of the proposed SSWC approach is illustrated in Section IV. Section V draws the conclusions.

II. PROBLEM FORMULATION

The IEEE 802.16m standard for next generation mobile BWNs is designed to support advanced services with higher data rate and higher mobility. In the meanwhile, an improved power-saving mechanism is desired for enhancing the energy conservation of MSs. In order to contend with aforementioned disadvantages of PSC I and to provide a flexible sleep mode operation, two significant notions are specified in IEEE 802.16m systems description document (SDD) [8]:

1) ***Listening window adjustment.*** During listening windows, the MS is expected to transmit/receive data or management messages based on the same manner as in the state of normal operations. The length of each listening window can be dynamically adjusted based on traffic availability or control signaling.
2) ***Sleep mode parameter update.*** The BS or MS may dynamically update the parameters of sleep mode operation (e.g., length of sleep window) based on the change of traffic patterns. The updating procedure may be executed without deactivating the sleep mode.

Based on these notions of IEEE 802.16m systems, the sleep mode operation for an MS can be modeled as a sleep windows selection (SWS) problem that is composed of multiple operations of control cycles. The definition of control cycle and the problem statement are described as follows:

Definition 1 (Control Cycle). *Given a BS and an MS that expects to enter the sleep mode or has stayed in the sleep mode, a control cycle C_i is defined as a time duration consisting of a decision epoch d_i, a sleep window SW_i, and a listening window LW_i. The BS determines the length of the sleep window SW_i at the decision epoch d_i. The MS stays in the sleep state during the sleep window SW_i and wakes up for data transportation in the listening window LW_i.*

Problem 1 (Sleep Windows Selection Problem). *Given a non-real-time downlink traffic and a sequence of control cycles, how to select the length of sleep window under the tolerable packet delay δ for each control cycle in order to maximize the energy efficiency for the MS?*

III. PROPOSED STATISTICAL SLEEP WINDOW CONTROL (SSWC) APPROACH

In order to resolve the target SWS problem, the SSWC approach is proposed, which determines the length of each sleep window appropriate for present traffic state and tolerable delay. It is intuitive that the length selection for each sleep window is dominated by the knowledge of the present traffic patterns, e.g., packet arrival time and packet arrival rate. However, it is difficult to obtained this information from the non-real-time traffic, only the number of buffered packets that arrived during the previous control cycle can provide hits to estimate the current traffic state. In the proposed SSWC approach, therefore, a POMDP is exploited to conjecture the present state of non-real-time traffic at each decision epoch. Based on the properties of POMDP, the optimal policy for solving the SWS problem is acquired in the SSWC approach. The details are explained in the following subsections.

A. Traffic Model

A discrete-time Markov-modulated Poisson process (dMMPP) is more general than the traditional Poisson model and is able to capture the characteristics of Internet traffic [9] [10]. In the proposed SSWC approach, therefore, the non-real time downlink traffic is modeled as a dMMPP with state space $\mathcal{S} = \{s_1, s_2, \cdots, s_M\}$, which can be represented by a transition probability matrix $\mathbf{P}$ of the Markov chain and a matrix $\mathbf{\Lambda}$ of Poisson arrival rate. These matrices are defined as

$$\mathbf{P} = \begin{bmatrix} p_{1,1} & \cdots & p_{1,M} \\ p_{2,1} & \cdots & p_{2,M} \\ \vdots & \ddots & \vdots \\ p_{M,1} & \cdots & p_{M,M} \end{bmatrix}, \quad \mathbf{\Lambda} = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_M \end{bmatrix}, \tag{1}$$

where $p_{i,j}$ represents the transition probability from state s_i to state s_j where $s_i, s_j \in \mathcal{S}$; while λ_i is the mean packet arrival rate in state s_i.

B. Traffic State Estimation

A POMDP model is formally described as a tuple $\langle \mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{Z}, \mathcal{O}, \mathcal{R} \rangle$, where $\mathcal{S}$ is a set of states, $\mathcal{A}$ is a set of actions, $\mathcal{T}$ is a set of state transition probabilities, $\mathcal{Z}$ is a set of observations, $\mathcal{O}$ is a set of observation probabilities, and $\mathcal{R}$ is a set of immediate rewards. For the proposed SSWC approach, the $\mathcal{S}$ and $\mathcal{T}$ correspond to the set of dMMPP states and its state transition probability matrix $\mathbf{P}$, respectively, as defined in the previous subsection. Since the objective of the SSWC approach is to resolve the SWS problem, the set of actions

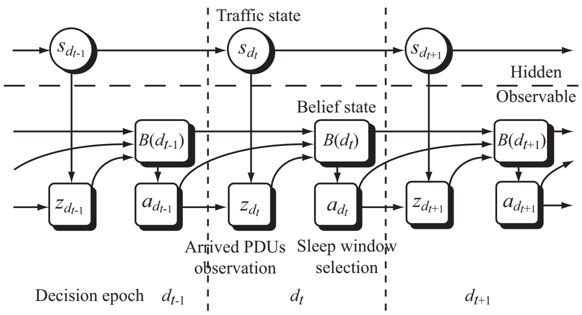

Fig. 2. Schematic diagram of POMDP model for SSWC approach.

is defined as $\mathcal{A} = \{a_1, a_2, \cdots, a_N\}$ where a_i represents the action of selecting the length T_{a_i} for a sleep window.

Considering a sequence of control cycle $\{C_1, C_2, \cdots, C_T\}$ in the proposed SSWC approach, the set of the corresponding decision epoches is defined as $\mathcal{D} = \{d_1, d_2, \cdots, d_T\}$. Fig. 2 depicts the schematic diagram of the POMDP model for the proposed SSWC approach. At each decision epoch $d_t \in \mathcal{D}$, the traffic state $s_{d_t} \in \mathcal{S}$ is hidden while the number of packets that arrived during the previous control cycle C_{t-1} is observed. Thus the set of observations is considered as $\mathcal{Z} = \{z_1, z_2, \cdots, z_Q\}$ where z_i denotes the number of packets arrived in the interval between two successive decision epoches. The observation probability can be expressed as

$$\begin{aligned} o(a_{d_{t-1}}, s_{d_t}, z_{d_t}) &\triangleq Pr(z_{d_t} | a_{d_{t-1}}, s_{d_t}) \\ &= \frac{\lambda_{d_t} T_{a_{d_{t-1}}}}{z_{d_t}} e^{-(\lambda_{d_t} T_{a_{d_{t-1}}})}, \end{aligned} \tag{2}$$

which is a conditional probability of an observation $z_{d_t} \in \mathcal{Z}$ at decision epoch d_t given the action $a_{d_{t-1}} \in \mathcal{A}$ made at d_{t-1} and the present traffic state $s_{d_t} \in \mathcal{S}$ at d_t. It is intuitive that the length of sleep window can be determined based on the last observation of arrived packets. However, there may be no optimal solution of this policy in a POMDP model [7].

For the purpose of acquiring the optimal policy, a belief state is introduced in the PDMDP model. Given a decision epoch $d_t \in \mathcal{D}$, the belief state is defined as $\mathcal{B}(d_t) = \{b(s_1^{d_t}), b(s_2^{d_t}), \cdots, b(s_M^{d_t})\}$, which represents the estimated probability distribution over the set of traffic states $\mathcal{S}$. Each element $b(s_i^{d_t})$ denotes the probability of traffic state s_i at decision epoch d_t. It is noted that $b(s_i^{d_t}) \geq 0, \forall s_i \in \mathcal{S}$ and $\sum_{\forall s_i} b(s_i^{d_t}) = 1, \forall d_t \in \mathcal{D}$ since the traffic must reside in one of the states within the $\mathcal{S}$ at any given decision epoch. As shown in Fig. 2, the belief state $\mathcal{B}(d_t)$ is updated at decision epoch $d_{t+1} \in \mathcal{D}$ by exploiting previous action $a_{d_t} \in \mathcal{A}$ and the corresponding observation $z_{d_{t+1}} \in \mathcal{Z}$. Thus each element $b(s_i^{d_{t+1}})$ of the belief state $\mathcal{B}(d_{t+1})$ can be derived using the Bayes rule as

$$\begin{aligned} b(s_i^{d_{t+1}}) &= Pr(s_i^{d_{t+1}} | \mathcal{B}(d_t), a_{d_t}, z_{d_{t+1}}) \\ &= \frac{o(s_i^{d_{t+1}}, a_{d_t}, z_{d_{t+1}}) \sum_{s_j^{d_t} \in \mathcal{S}} p_{i,j} b(s_j^{d_t})}{\sigma(\mathcal{B}(d_t), a_{d_t}, z_{d_{t+1}})}, \end{aligned} \tag{3}$$

where

$$\begin{aligned} \sigma(\mathcal{B}(d_t), a_{d_t}, z_{d_{t+1}}) &\triangleq Pr(z_{d_{t+1}} | a_{d_t}, \mathcal{B}(d_t)) \\ &= \sum_{s_j^{d_t} \in \mathcal{S}} \sum_{s_i^{d_{t+1}} \in \mathcal{S}} b(s_j^{d_t}) p_{i,j} o(s_i^{d_{t+1}}, a_{d_t}, z_{d_{t+1}}). \end{aligned} \tag{4}$$

It can be observed that the belief state is a summary statistic for the entire history of the process, which incorporates the action and the corresponding observation at each decision epoch progressively. Based on the belief states, the more precise traffic state can be estimated for determining the proper length of sleep windows.

C. Cost Evaluation

In order to provide the optimal policy for solving the SWS problem, some costs or rewards should be defined for each action $a_k \in \mathcal{A}$ taken in state $s_i \in \mathcal{S}$. Two cost metrics, including energy cost and packet delay, are considered in the proposed SSWC approach. Both of the two metrics are defined as follows:

1) Energy Cost: To evaluate the power consumption for an MS in the sleep mode, the *energy cost* is defined as the average energy consumption per frame during a control cycle. Let ε_{SW} and ε_{LW} denote the energy consumption per frame within the sleep window and listening window, respectively. Moreover, the energy consumption of switching between listening window and sleep window is considered as ε_S. The expected energy cost for an action $a_k \in \mathcal{A}$ taken in state $s_i \in \mathcal{S}$ can be expressed intuitively as

$$\overline{E}(s_i, a_k) = \frac{2\varepsilon_S + \varepsilon_{SW} E[T_{SW}(s_i, a_k)] + \varepsilon_{LW} E[T_{LW}(s_i, a_k)]}{E[T_{SW}(s_i, a_k)] + E[T_{LW}(s_i, a_k)]}, \tag{5}$$

where $E[T_{SW}(s_i, a_k)]$ and $E[T_{LW}(s_i, a_k)]$ represents the expected length of the sleep window and the followed listening window, respectively. Since the action a_k is taken in state s_i, the length of sleep window $E[T_{SW}(s_i, a_k)] = T_{a_k}$; while the $E[T_{LW}(s_i, a_k)]$ can be derived as

$$E[T_{LW}(s_i, a_k)] = (N_{\lambda_i, a_k}^{SW} + N_{\lambda_i, a_k}^{LW}) E[U], \tag{6}$$

where N_{λ_i, a_k}^{SW} and N_{λ_i, a_k}^{LW} represents the average number of arriving packets during the sleep window and the listening window, respectively. Let U be the random variable of service time for each packet and $E[U] = 1/\mu$ is the mean service time. By applying the Little's theorem [11], N_{λ_i, a_k}^{SW} and N_{λ_i, a_k}^{LW} can be expressed as

$$N_{\lambda_i, a_k}^{SW} = \lambda_i T_{a_k}, \;\; N_{\lambda_i, a_k}^{LW} = \lambda_i E[T_{LW}(s_i, a_k)]. \tag{7}$$

By substituting (7) and $E[U] = 1/\mu$ into (6), the length of listening window while an action a_k taken in state s_i can be obtained as

$$E[T_{LW}(s_i, a_k)] = \frac{\lambda_i T_{a_k}}{\mu - \lambda_i}. \tag{8}$$

2) Packet Delay: During the sleep window, the arriving packets are buffered at the BS and will be transmitted to the

MS within the subsequent listening window. For the purpose of satisfying the QoS requirement in terms of delay constraint, the *packet delay* is defined as the time duration between the instant of packet arrived at the MAC in the BS and the instant of the packet transmitted completely. Since the packet arrival follows the Poisson distribution in each state and the service rate is assumed as general distribution, the $M/G/1$ queueing model is considered to describe the packet arrival and departure. The expected packet delay for an action $a_k \in \mathcal{A}$ taken in state $s_i \in \mathcal{S}$ can be expressed as

$$\overline{D}(s_i, a_k) = E[D_{SW}(s_i, a_k)] + E[D_{LS}(s_i, a_k)] + E[U], \tag{9}$$

where $E[D_{SW}(s_i, a_k)]$ represents the average remaining length of sleep window for the packet; while the expected waiting time of the packet during the listening window is denoted as $E[D_{LW}(s_i, a_k)]$. According to $M/G/1$ with server vacation, the $E[D_{SW}(s_i, a_k)]$ can be obtained as

$$E[D_{SW}(s_i, a_k)] = \frac{E[T_{SW}(s_i, a_k)^2]}{2E[T_{SW}(s_i, a_k)]} = \frac{T_{a_k}}{2}. \tag{10}$$

On the other hand, based on Pollaczek-Khintchine mean value formula [11] and Little's theorem, the $E[D_{LW}(s_i, a_k)]$ can be derived as

$$E[D_{LW}(s_i, a_k)] = \frac{\lambda_i E[U^2]}{2(1-\rho_i)}, \tag{11}$$

where $\rho_i \triangleq \lambda_i/\mu$ denotes the traffic intensity.

Since the objective of the proposed SSWC approach is to maximize the energy efficiency for the MS under the consideration of delay constraint δ, the set of immediate rewards $\mathcal{R}$ can be calculated via the *Cost Assignment Algorithm* as illustrated in Algorithm 1. The immediate reward $r(s_i, a_k)$ for $a_k \in \mathcal{A}$ taken in $s_i \in \mathcal{S}$ is defined as the expected energy cost derived from (5) if it satisfies the tolerable delay δ (as in lines 5 and 6 of the Algorithm 1). Otherwise, a pre-defined value $\overline{E}_{max}$ is assigned for representing the acute cost, i.e., lines 3 and 4 in the Algorithm 1.

Algorithm 1: *Cost Assignment Algorithm*

```
Input: $\mathcal{S}$, $\mathcal{A}$, and tolerable delay $\delta$
Output: set of immediate rewards $\mathcal{R}(\mathcal{S}, \mathcal{A})$
1 foreach $s_i \in \mathcal{S}$ do
2     foreach $a_k \in \mathcal{A}$ do
3         if $\overline{D}(s_i, a_k) > \delta$ then
4             $r(s_i, a_k) \leftarrow \overline{E}_{max}$
5         else
6             $r(s_i, a_k) \leftarrow \overline{E}(s_i, a_k)$
7         end
8     end
9 end
```

D. Window Selection Policy

In the proposed SSWC approach, the length of each sleep window is selected at each decision epoch according to the present traffic state and tolerable packet delay. Thanks to the belief states of the POMDP model, the uncertain traffic states can be estimated. On the other hand, the energy cost of an action taken in a state are provided by the set of immediate rewards. Based on these two types of information, a T-step value function is adopted to obtain the corresponding action that results in the minimum energy consumption for the MS. The T-step value function for a decision epoch d_t can be obtained as in (12) at the top of the next page, which starts with $d_t = 0$ and ends the recursion with $d_t = T - 1$, and letting $V_T(b(s_i^T)) = 0$ for $\forall s_i \in \mathcal{S}$. The first item of (12) denotes the reward for a belief state $b(s_i^{d_t}) \in \mathcal{B}(d_t)$; while the expected reward of the future belief state $b(s_i^{d_{t+1}}) \in \mathcal{B}(d_t)$ is represented in the second item. The γ is denoted as a discount factor for convergence control of the value function. In other words, the action is selected according to its energy cost for the current state and the energy costs of the future actions taken in the successive states. According to the T-step value function, the optimal policy for selecting the proper length of each sleep window is acquired. Consequently, the proposed SSWC approach provides an optimal solution for resolving the SWS problem.

IV. PERFORMANCE EVALUATION

In this section, simulations are conducted to evaluate the performance of the proposed SSWC approach in comparison with the IEEE 802.16e PSC I and the inferred IEEE 802.16m power-saving mechanism. It is noted that the inferred IEEE 802.16m power-saving mechanism is defined as a scheme that follows the notions of IEEE 802.16m sleep mode operation and exploits the configuration of PSC I. In other words, all the processes of the inferred mechanism are the same as that of PSC I expect for the period of data transportation. In the inferred scheme, the buffered packets will be received by the MS during the adjustable listening windows in the sleep mode instead of returning to the normal mode. A single BS/MS pair with a non-real-time downlink traffic is considered as the simulation scenario. The simulation is implemented via MATLAB event-driven simulator. Each obtained result is average from 100 simulation runs, where each simulation run for 10 minutes. The parameters adopted within the simulations are listed as follows: $\mu = 3$ packets/frame, $\varepsilon_{LW} = 280$ mW, $\varepsilon_{SW} = 10$ mW and $\varepsilon_S = 1$ mW [12].

Fig. 3 shows the performance comparison among the proposed SSWC approaches with different delay constraints δ over various packet arrival rates. It is observed that all the curves of the SSWC approaches satisfy the corresponding delay constraints, respectively, because the cost assignment algorithm successfully eliminates the unsuitable actions for sleep windows selection. On the other hand, the SSWC approach with lower delay constraint has lower packet delay but incurs the higher energy consumption. This can be attributed to the reason that the MS is provided with a series of alternate

$$V_{d_t}(b(s_i^{d_t})) = \min_{a_k^{d_t} \in \mathcal{A}} \left[\sum_{s_i^{d_t} \in \mathcal{S}} b(s_i^{d_t}) r(s_i^{d_t}, a_k^{d_t}) + \gamma \sum_{z_j^{d_{t+1}} \in \mathcal{Z}} \sigma(\mathcal{B}(d_t), a_k^{d_t}, z_j^{d_{t+1}}) V_{d_{t+1}}(b(s_i^{d_{t+1}})) \right] \qquad (12)$$

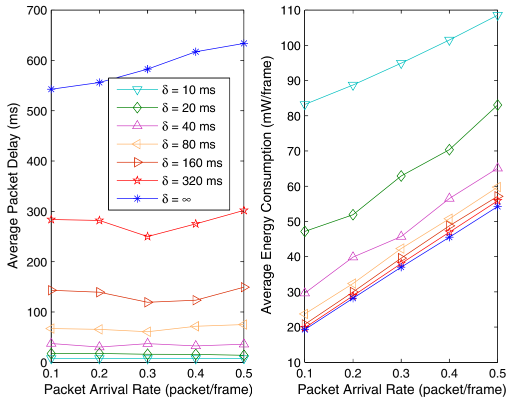

Fig. 3. Performance comparison among the proposed SSWC approaches with different delay constraints δ over various packet arrival rates.

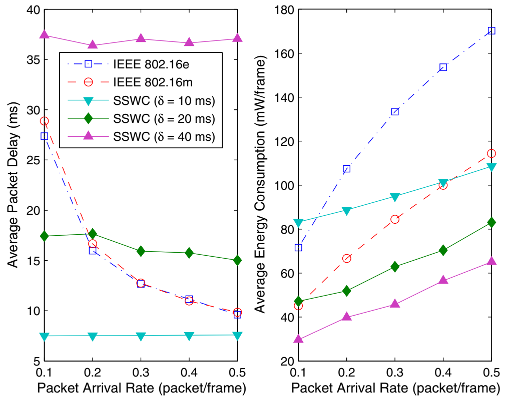

Fig. 4. Performance comparison among IEEE 802.16e, IEEE 802.16m, and SSWC approaches over various packet arrival rates.

sleep windows and listening windows in the sleep mode. Since the lower packet delay comes from the shorter length of sleep window, the more number of listening windows is presented in the simulation duration, which consequently increase the energy consumption.

The performance comparison among the IEEE 802.16e PSC I (as IEEE 802.16e), the inferred IEEE 802.16m power-saving mechanism (as IEEE 802.16m), and the proposed SSWC approaches are illustrated in Fig. 4. As can be expected that the IEEE 802.16m outperforms the IEEE 802.16e in terms of the energy consumption since the MS is always staying in the sleep mode without the existence of idle periods. On the other hand, at packet arrival rate of 0.2, the SSWC ($\delta = 20$ ms) has slightly higher packet delay than the IEEE 802.16e and IEEE 802.16m schemes, but the relatively lower energy consumption of it is presented. This is because that the optimal length of each sleep window is selected under the tolerable delay constraint in the SSWC approach, which consequently minimizes the energy consumption. Due to the same reason, in the packet arrival rate of 0.4, the similar amount of energy is consumed by the SSWC ($\delta = 10$ ms) and the IEEE 802.16m respectively, but the SSWC ($\delta = 10$ ms) has a lower packet delay than the IEEE 802.16m scheme.

V. CONCLUSIONS

In this paper, a statistical sleep window control (SSWC) approach is proposed to maximize the energy efficiency by selecting the length of sleep windows appropriate for the traffic states. A partially observable Markov decision process is exploited in the SSWC approach to conjecture the present traffic state and consequently provides the optimal selection policy. Simulation studies show that the proposed SSWC approach outperforms the IEEE 802.16e PSC I and the inferred IEEE 802.16m power-saving mechanism.

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