國 立 交 通 大 學

電信工程研究所

碩 士 論 文

針對 IEEE 802.16 寬頻無線網路的睡眠模式運作之效能分析及以部分可探測馬可夫判斷過程為基礎之睡眠訊框決策

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中 華 民 國 九 十 九 年 十 月

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碩 士 論 文

A Thesis
Submitted to Institute of Communications Engineering
College of Electrical and Computer Engineering
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Master of Science
in

Communications Engineering

October 2010

Hsinchu, Taiwan, Republic of China

中華民國九十九年十月

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摘　　要

IEEE 802.16 標準是為了支援下一代無線寬頻存取網路中高資料率及高移動性之服務而發展出來的。在這一系列的標準當中，為了使行動裝置可達到節能的目的，具體制訂了一些睡眠模式運作的機制。在本論文中，首先分別針對 IEEE 802.16e 以及 IEEE 802.16m 提出分析模型，其中下行（downlink）與上行（uplink）鏈路傳輸所造成的效果，皆被審慎納入分析模型的考慮當中，並在隨後利用模擬以驗證這些模型的有效性。然而，根據 IEEE 802.16e/m 兩系統之省電效能評估的結果，可以發現由既有機制（例如：頻繁的狀態切換、使用率低的聆聽訊框、以及利用二進制指數成長的睡眠訊框長度）所產生的效能低下。因此，此論文提出一個以部分可探測馬可夫判斷過程為基礎之睡眠訊框決策(PSWD)方式，其可利用目前傳輸鏈路之統計特性，決定出每個睡眠訊框適合的長度。而根據目前傳輸鏈路之狀態，且考慮到可容忍之網路延遲之下，PSWD 提供一個以耗能為基準的睡眠訊框決定策略。模擬結果可顯示出 PSWD 方法在節能方面優於傳統的 IEEE 802.16e/m 省電機制，並且同時滿足不同傳輸需求所對應到之延遲限制。

Comprehensive Performance Analysis and POMDP-based Sleep Window Determination for IEEE 802.16 Broadband Wireless Networks

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Abstract

The IEEE 802.16 standard is developed to support services with high data rate and high mobility for the next generation broadband wireless access networks. There are existing sleep mode operations specified in the series of IEEE 802.16 standards in order to provide energy conservation for the mobile devices. In this work, the analytical models for the sleep mode operations of both the IEEE 802.16e and IEEE 802.16m standards are proposed respectively. The effects of both downlink and uplink traffic are properly considered in the proposed models. Simulations are performed in order to validate the effectiveness of the proposed system models. However, according to the performance evaluation for the IEEE 802.16e/m system, inefficiency is observed which can be resulted from specific mechanisms within the sleep mode operations, such as frequent state transitions, under-utilized listening windows, and the adoption of binary-exponential growth of sleep window size. A POMDP-based sleep window determination (PSWD) approach is proposed in this thesis, which stochastically determines the adequate length of each sleep window according to the traffic pattern. Based on the estimated traffic state, an energy cost-based sleep window determination policy is provided within the PSWD approach in consideration of tolerable network delays. Simulation results show that the proposed PSWD approach outperforms the conventional IEEE 802.16e/m power-saving mechanisms in terms of energy conservation while the delay constraints are also satisfied with various traffic demands.

誌　　　謝

一篇論文的完成，所代表的不僅是兩年研究生涯劃下了句點，其中更包含了學業上的歷練、生活經驗上的積累、以及身旁家人、師長及朋友的鼓勵與協助。

在此我首要感謝張仲儒教授及王蒞君教授特地撥冗擔當俊宇的學位考試委員，兩位老師於口試時的指導與批評，使得這份論文內容不盡完美之處得以改善，也讓我體會到電信這個領域之博大精深、自己的研究在整個學術大海中的渺小與微不足道。另外，我更想謝謝指導教授方凱田老師，剛進入碩班時由老師引導我進入當時最熱門的 WiMAX 之大門，並多次帶著我前往合作企業進行報告與參觀，我在那裡體會學習到了許多，像是報告技巧、待人處事、以及公司內部運作與氣氛等等，可說碩士生涯一大半的收穫都來自於此，這可能是光在實驗室中無從得到的。

實驗室的前輩：建華、柏軒、佳仕及裕彬學長們，在研究與課業甚至生活上給了我不少建議與幫助，尤其同組的文俊及仲賢學長，更是我常諮詢的活字典，也特別感謝仲賢學長雖已畢業投入職場，仍於百忙之中協助批改我的研討會論文，讓我有機會參與 PIMRC 國際會議增廣視野。而同為 97 級的伙伴們：萬邦、承澤、與其懋同學，從大學即同校以來六年的深厚情誼，使我們彼此不僅在課業及研究上相互扶持打氣，更在研究之餘留下了不少歡樂和難忘的回憶，我們終於達陣了，可喜可賀！實驗室的學弟妹們：惟能、劭凱、宥儒、瑞鴻、及昭華，祝福你/妳們能夠在 MINT LAB 研究順利成功且獲得比我們更加豐碩的成果；更年輕的裕平、智偉、景維、修銘、及族繁不及備載的學弟妹，前面的路還很長，希望你們能夠漸漸發掘並享受研究的樂趣。還要提到一路情義相挺陪伴我多年的死黨：聖鈞、善淳、育誠、家峻、智翔與達偉，謝謝你們幫忙分擔壓力且不時給予我鼓勵。

最後，我最感激的，還是莫過於陪我走過這段漫長時光的家人，爸爸、媽媽、和弟弟，他們是我最溫暖的依靠，也是遭遇挫折時最有力的精神支柱。

這本論文，獻給以上的大家，及曾經幫助我、鼓勵我的好朋友們。

陳俊宇謹誌 于國立交通大學 新竹

民國九十九年九月

Special thx to 3-10 20, 24-25 25, 3-8 23

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Chapter 1

Introduction

The IEEE 802.16 working group has drawn up a series of standards for wireless metropolitan area networks (WMANs) and next generation broadband wireless access systems. The IEEE 802.16-2004 [1] specifies the access between a base station (BS) and fixed subscriber stations (SSs); while movable mobile stations (MSs) are further supported by the IEEE 802.16e [2], which lead to the issues of energy-saving and handover. The IEEE 802.16-2009 [3] consolidates the two standards above and adds additional management information. The latest progress under standardization is the IEEE 802.16m [4] which is developed to achieve the requirements for future IMT-Advanced networks with higher data rate and higher mobility. Since mobility is considered a key feature in wireless networks, how to prolong the battery lifetime of MSs has been recognized as one of the critical issues.

The sleep mode of IEEE 802.16 systems, first introduced by the IEEE 802.16e standard, is aimed to conserve the energy of MSs. By means of a pre-negotiation process, an MS can be absent from the air interface of its serving BS. In other words, the MS may power down some physical operation components or perform other activities that do not require communication with the BS. Three types of power-saving classes (PSCs) are defined in the sleep mode to satisfy demands for packets with different traffic patterns. The PSC of Type I with binary-exponential growing sleep windows is suitable for both best-effort (BE) and non-real-time variable-rate (NRT-VR) service flows; while quality-of-service (QoS) guaranteed services, including unsolicited grant service (UGS) and real-time variable-rate (RT-VR) traffic, are recommended to the PSC of Type II, wherein the length of each sleep window is constant along with the periodic occurrence of transmission-allowed listening windows. The PSC of Type III is appropriate for multicast connections and control management signals. It is noted that connections having similar traffic properties are gathered into a single PSC. Multiple connections with distinct PSCs may exist between a single pair of an MS and its serving BS. Furthermore, for the case that there are mixed real-time and non-real-time traffic, constant length of sleep windows will be adopted in order to guarantee the QoS requirements of real-time traffic [5] [6].

There are several works focused on the performance analysis and modeling of the IEEE 802.16e sleep mode operation. Xiao [7] and Zhang [8] set up analytical models for the sleep mode with the Poisson arrival process and the hyper-Erlang distribution, respectively. A traffic model with mixture exponential distribution is utilized by J. Almhana et al. [9] to approximate packets inter-arrival times, which possess the characteristics of heavy-tailed distributions. On the other hand, in the work of [10], Y. Park et al. model the system by an M/G/1/K finite queue with multiple server vacations. Moreover, the research proposed in [11] fully considers the mixed effect from both downlink (DL) /uplink (UL) traffic and multiple connections between an MS and its serving BS in the IEEE 802.16e power-saving operation. The sleep mode with generalized traffic processes is analyzed in [12], wherein an enhanced scheme is also addressed to improve the performance of power management by adjusting the trade-off between energy consumption and packet delay. From the analytical results of these studies, it can be realized that the inefficiency of the IEEE 802.16e comes from the configuration of sleep mode operation, e.g. the mechanism of binary-exponential traffic detection, and frequent transitions between sleep modes and normal modes. Hence some enhanced sleep mode mechanisms have been designed, e.g. the work in [13] [14] dynamically adjust the length of initial sleep window in order to reduce the number of unused listening windows resulted from the binary-exponential growing of sleep windows; while the adaptively control of the initial and final sleep windows is proposed in [15]. For the sake of improving the power-saving efficiency of MSs, some notions of sleep mode mechanism are also proposed in the IEEE 802.16m by the IEEE 802.16 working group. The IEEE 802.16m adopts the virtues of the sleep mode operation in the IEEE 802.16e, such as the allowance of transmission within the listening windows of PSC of Type II, and gets rid of the aforementioned disadvantages.

As for the sleep mode of the new IEEE 802.16m standard, a few studies have been investigated. In [16], the authors deploy a modified M/D/1 system with vacations to evaluate message delays and MS's power consumption in DL channels. On the other hand, a two-dimensional Markov chain is constructed by Baek et al. [17] to model the sleep mode operation for DL traffic and to analyze the average power consumption of MSs. The authors of [18] propose a new sleep mode scheme with periodically-sent traffic indication messages in order to trace traffic more precisely. However, the influence of UL traffic on the IEEE 802.16m sleep mode operation has not been investigated in the existing literature. In this work, based on the concept of [11], analytical models for both the IEEE 802.16e and IEEE 802.16m sleep mode operations are proposed. The integrated effect of DL and UL service flows are investigated in order to evaluate sleep ratio and mean packet delay of both PSC of Type I and Type II. The performance of the proposed analytical model is evaluated and validated via simulation studies. However, inefficiency can still be observed from the existing mechanism of sleep mode operation in IEEE 802.16m system which can be improved accordingly.

A partially observable Markov decision process (POMDP) model is suitable for the purpose of conjecturing the unobservable present traffic state. Therefore, in this thesis, a POMDP-based sleep window determination (PSWD) approach is proposed in order to improve the performance of energy conservation in the IEEE 802.16m systems. Based on the present traffic state with consideration of tolerable delay, the proposed PSWD approach determines the appropriate length of each sleep window. In accordance with the rewards calculated via POMDP formulation, an energy cost-based sleep window determination policy can be acquired. The efficiency of proposed PSWD approach is evaluated via simulations in terms of average energy cost and mean packet delay. Simulations results show that the proposed PSWD approach outperforms the IEEE 802.16e/m systems in the aspect of energy conservation while the delay constraints are also fulfilled under various traffic demands.

The rest of the thesis is organized as follows. Chapter 2 briefly introduces the IEEE 802.16e and IEEE 802.16m sleep mode operations respectively, and the comparisons between these two mechanisms.. The proposed analytical models for these two standards are described in Chapter 3; while the performance analysis of the models are investigated in Chapter 4. The detailed procedures of proposed PSWD approach are described in Chapter 5. Chapter 6 validates the effectiveness of the two analytical models and conducts the performance evaluation of proposed PSWD method. Chapter 7 draws the conclusion.

Chapter 2

Preliminary

In this chapter, the behavior of sleep mode operations of the IEEE 802.16e and the IEEE 802.16m are introduced separately by the following sections, and some comparisons between the two standards are drawn afterwards.

2.1 IEEE 802.16e Sleep Mode Operation

Fig. 2.1 shows a schematic diagram of the IEEE 802.16e power-saving mechanism, which includes both the normal mode and the sleep mode. The MS enters the sleep mode while it has been idle for a predefined idle period τ and negotiates with the BS by a request message MOB_SLP-REQ and an approval message MOB_SLP-RSP in the normal (active) mode. Within the sleep mode, a series of sleep cycles are provided for the MS. Each sleep cycle consists of a sleep window followed by a listening window with fixed time duration. In other words, the length of the nth sleep cycle can be represented as $T_{C_n} = T_{S_n} + T_L$, where T_{S_n} denotes the length of the sleep window at the nth sleep cycle; while T_L indicates the length of a listening window. According to the IEEE 802.16e standard for PSC of Type I, the MS is designed to be in the awake state within the listening windows for examining the MOB_TRF-IND message, which

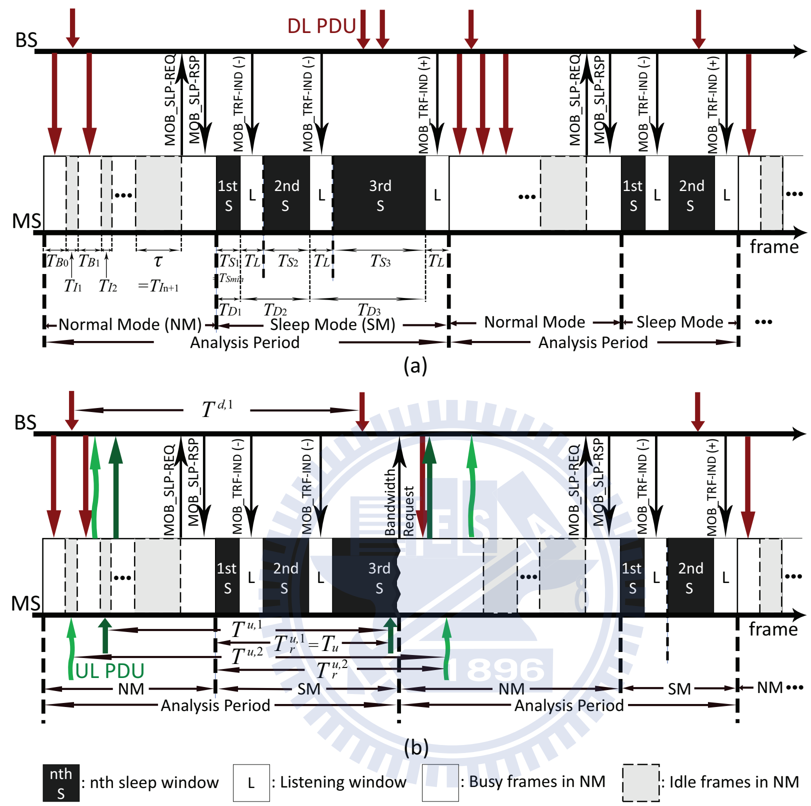

Figure 2.1: Schematic diagram of sleep mode operation for PSC of Type I in IEEE 802.16m: (a) with regular termination and (b) with interrupted termination

is a traffic indication message broadcasted from the BS. In the case that there are no DL packets destined for the MS, MOB_TRF-IND will be given a negative value in the field corresponding to the MS. Upon receiving the negative MOB_TRF-IND, the MS will continue staying in the sleep mode. When consecutive negative traffic indication messages are obtained by the MS, the length of its sleep window will be doubled from the previous one until the maximum size of sleep window is reached, which can be represented as

$$T_{S_n} = \min(2^{n-1} \cdot T_{S_{min}}, T_{S_{max}}) \tag{2.1}$$

where $T_{S_{min}}$ and $T_{S_{max}}$ are the initial (minimum) and the maximum sleep window sizes defined by the pre-negotiated MOB_SLP-REQ and MOB_SLP-RSP messages. Furthermore, the reference period of each traffic indication message is called the detection window. The length of the detection window at the nth sleep cycle (as in Fig. 2.1(a)) is defined as

$$T_{D_n} = \begin{cases} T_{S_n} & \text{for } n = 1 \\ T_L + T_{S_n} & \text{otherwise.} \end{cases} \tag{2.2}$$

In the case there are DL data bursts addressed to the MS arriving during a specific detection window, the serving BS will buffer these packets until the subsequent listening window of the MS. Thereupon a positive MOB_TRF-IND will be sent in order to inform the MS of the arrived packets. Once receiving the positive traffic indication message, the MS will consequently return into the normal mode afterwards. Specifically, provided that any UL packet is ready for being transmitted, the sleep mode of the MS will be terminated and switched to the normal mode immediately.

The characteristics of the PSC of Type II is similar to that of Type I except for

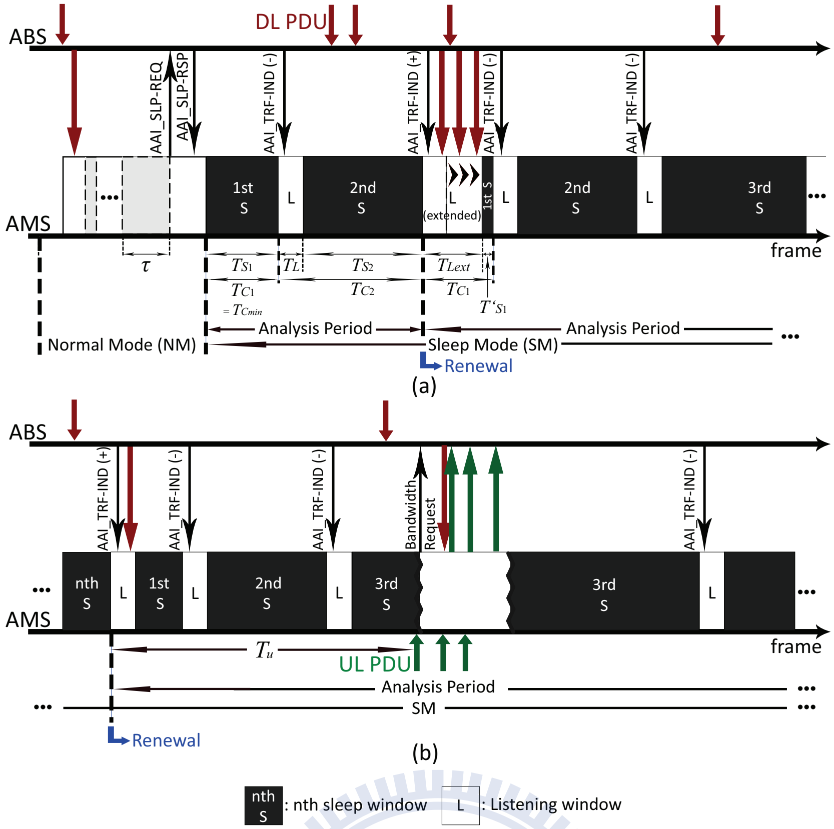

Figure 2.2: Schematic diagram of sleep mode operation for IEEE 802.16m: (a) with DL traffic and (b) with DL and UL traffic.

the following differences: (a) the sleep window becomes fixed time duration, which is redefine as $T_{S_n} = T_{S_{min}}$, and (b) Packet transmission is allowed within the listening window. Moreover, so long as the amount of packets does not exceed the capacity of the listening window, it is unnecessary for the MS to deactivate the ongoing sleep mode.

2.2 IEEE 802.16m Sleep Mode Operation

The sleep mode operation of the IEEE 802.16m is illustrated in Fig. 2.2 by two examples. The terms *advanced BS (ABS)* and *advanced MS (AMS)* indicate a BS and an MS that support the functions of the IEEE 802.16m, respectively. Moreover, in the following paragraphs, IEEE 802.16e and IEEE 802.16m are represented as 16e and 16m for the convenience of description. As shown in Fig. 2.2(a), the sleep mode mechanism of 16m is almost similar to that of 16e in Fig.. However, it is contrary to 16e that each sleep cycle is composed of a listening window followed by a sleep window except for the first one, which contains only a sleep window. Therefore, the length of the nth sleep cycle of 16m can be represented as

$$T_{C_n} = \begin{cases} T_{S_n} & \text{for } n = 1 \\ T_L + T_{S_n} & \text{otherwise} \end{cases} \tag{2.3}$$

where T_{S_n} denotes the length of the regular sleep window at the nth sleep cycle; while T_L is the default length of a listening window.

During the sleep mode of 16m, the AMS shall also wake up at every listening window and check the value of the traffic indication message AAI_TRF-IND so as to determine whether there is incoming DL traffic buffered at the ABS or not. In case of receiving the negative AAI_TRF-IND, the AMS then goes into the sleep window for the rest of the current sleep cycle. Furthermore, the length of the *sleep cycle* (instead of sleep window as in 16e) will be twice the length of the previous one until the maximum sleep cycle, which can thus be expressed as

$$T_{C_n} = \min(2^{n-1} \cdot T_{C_{min}}, T_{C_{max}}) \tag{2.4}$$

where $T_{C_{min}}$ and $T_{C_{max}}$ are the length of the initial sleep cycle and the maximum sleep cycle respectively. Moreover, the nth detection window T_{D_n} is just equal to the nth sleep cycle, that is, $T_{D_n} = T_{C_n}$.

On the other hand, as for the positive AAI_TRF-IND received, the length of the current sleep cycle shall be renewed to the initial sleep cycle, as the points "Renewal" marked in Fig. 2.2. Accordingly, the *listening window* in this cycle is used to receive the buffered DL data or transmit the AMS's own UL packets without the need of returning to the normal mode. If all the packets can be transmitted completely during the listening window, its length will be equal to default T_L (as shown in the first sleep cycle of Fig. 2.2(b)). Otherwise, extension of the listening window will be conducted in order to satisfy the demand of transmission as depicted in Fig. 2.2(a), where $T_{L_{ext}}$ is the length of the extended listening window. It is noticed that the limit of extension is constrained by the end of the sleep cycle where the listening window is located.

The sleep mode mechanism described above is recommended for BE traffic, and the name "Type I" is given here in contrast with the similar operation of PSC of Type I for 16e. On the other hand, "Type II" of 16m is referred to the operation with fixed-duration sleep cycles, i.e., $T_{C_n} = T_{C_{min}}$, which is suitable for real-time traffic-only or real-time and BE-traffic mixed scenarios.

The AMS will keep staying in the sleep mode, and the process described above will be iterated until an explicit termination is introduced by the AMS or the ABS.

2.3 Improvements in Sleep Mode Operations of IEEE 802.16m on IEEE 802.16e

As can be observed from Fig. 2.1, a series of alternative of normal modes and sleep modes are operated by the MS of 16e. The MS always tends to deactivate the sleep mode and return to the normal mode for the sake of data transmission, then wait for another idle period and reactive the sleep mode. This configuration is inferred as the major cause of inefficiency for energy conservation in 16e. Furthermore, every time when reactivating the sleep mode, the initial length of the sleep will be reset to $T_{S_{min}}$, and continue to utilized a binary-exponential growing algorithm to detect incoming traffic. This will bring about a great deal of listening windows with low utilization, especially for listening windows of PSC of Type I in 16e, which merely function as checkpoints for traffic indication message. An evolutional sleep mode mechanism is developed in 16m in order to cope with aforementioned disadvantages of 16e, and a more flexible scheme for sleep mode operation is also provided. The major differences and improvements are summarized as follows:

- ***Concise sleep cycle setting***: In 16e, the operation of sleep cycles is determined by connection-based factors; while an AMS-based scheme is considered for 16m. A single sleep cycle setting, indicated by a sleep cycle ID (SCID), is applied among all the connections of an AMS in the 16m.

- ***Ongoing sleep mode parameter update***: An AMS of 16m may send/receive data and MAC control signaling, or update parameters (e.g. the length of a sleep window) without deactivating the sleep mode. In other words, the AMS does not have to wake up into the normal mode for the sake of data transmission, then wait for another idle period τ without issued traffic, exchange the MAC control messages, and return to the sleep mode again.

- ***Adjustable listening windows with higher utilization***: In 16m, all the listening windows of an AMS can be utilized to transmit packets, including DL and UL service flows. Moreover, the length of each listening window is adjustable depending on the amount of data need to be transferred.

- ***Consistent length of sleep cycles from UL transmission***: According to the specification of 16m [4], the interruption resulted from UL transmission at any time will have no impact on the length and phase of the sleep cycles, as shown in Fig 2.2(b). It means that an AMS shall resume the original paused sleep mode operation after accounting for the time elapsed during UL transmission.

Chapter 3

Modeling of Sleep Mode Operations

In the following sections, the mathematical system models of the 16e sleep mode operation is described in detail. After that, the similar technique is extended to analyze the mechanism of 16m[1]. Moreover, the analyses consider an error-free environment and there is sufficient bandwidth for the transmission related to the MS/AMS regardless of DL or UL traffic, so every packet and MAC control messages are transmitted successfully all the time.

3.1 Analytical Model for IEEE 802.16e

For analysis models of 16e, the *Analysis Period*is defined the interval between the starting point of the normal mode and the termination of the sleep mode, as illustrated in Fig. 2.1(a).

[1]The previous chapter points out all the discrepancy between Type I/Type II of 16e and 16m. The following paragraphs will adopt (if necessary) either the superscript "(e^{I})", "(e^{II})", "(m^{I})", or "(m^{II})" for distinguishing the notations between Type I/Type II of 16e or 16m, e.g. $T_{S_n}^{(e^{II})}$ and $T_{S_n}^{(m^{I})}$.

3.1.1 Power Saving Class of Type I

As shown in Fig. 2.1(b), the parameters $T^{d,i}$ and $T^{u,i}$ are defined as the packet inter-arrival times of the ith DL and UL connections; while their mean packet arrival rates are denoted as $\lambda^{d,i}$ and $\lambda^{u,i}$. It is assumed that $T_r^{u,i}$ represents the remaining inter-arrival time of $T^{u,i}$. According to the residue life theorem [19], the cumulative distribution function (CDF) of $T_r^{u,i}$ (denoted as $F_{T_r^{u,i}}(\cdot)$) can be expressed as

$$F_{T_r^{u,i}}(t) = \lambda^{u,i} \int_0^t [1 - F_{T^{u,i}}(x)]dx. \tag{3.1}$$

In the case that the traffic is assumed as the Poisson distribution, $F_{T_r^{u,i}}(t)$ as obtained from (3.1) can be rewritten as $F_{T_r^{u,i}}(t) = 1 - e^{-\lambda^{u,i}t}$. The minimum value of $T_r^{u,i}$ in terms of the various connections i can be denoted as $T_u \triangleq \min\{T_r^{u,i}\}_{i=1}^{n_u}$, where n_u is the total number of the UL connections within a power-saving class. Consequently, the CDF of T_u can be computed as

$$F_{T_u}(t) = 1 - \Pr[T_u > t] = 1 - \prod_{i=1}^{n_u} \left[1 - F_{T_r^{u,i}}(t)\right]. \tag{3.2}$$

Similarly, (3.2) can be simplified as $F_{T_u}(t) = 1 - e^{-\lambda_u t}$ while the Poisson traffic is assumed, where $\lambda_u = \sum_{i=1}^{n_u} \lambda^{u,i}$. For further exploitation, the following two parameters are defined: $\lambda_d \triangleq \sum_{i=1}^{n_d} \lambda^{d,i}$ and $\lambda \triangleq \lambda_u + \lambda_d$. It is noted that n_d is the total number of DL connections in a power-saving class. Due to the random property of a UL packet while it is available to be transmitted from the MS, it is required to define a random variable $T_{u,n}$ according to the nth sleep cycle which the the first arrival of UL packet arrives at, that is, where T_u lies in, i.e.

$$T_{u,n}^{(\mathrm{eI})} = \begin{cases} T_u & \text{if } S_{C_{n-1}} < T_u < S_{C_n} \\ 0 & \text{otherwise} \end{cases} \tag{3.3}$$

where $S_{C_n} = \sum_{i=1}^{n} T_{C_i}$. Consequently, its Probability Density Function (PDF) can be obtained as

$$f_{T_{u,n}^{(\mathrm{eI})}}(t) = \begin{cases} \frac{\lambda_u e^{-\lambda_u t}}{\int_{S_{C_{n-1}}}^{S_{C_n}} \lambda_u e^{-\lambda_u x} dx} & \text{if } S_{C_{n-1}} < T_u < S_{C_n} \\ 0 & \text{otherwise.} \end{cases} \tag{3.4}$$

As a result, the average value of $T_{u,n}$ can be computed as

$$\overline{T}_{u,n}^{(\mathrm{eI})} = \frac{\int_{S_{C_{n-1}}}^{S_{C_n}} x\lambda_u e^{-\lambda_u x} dx}{\int_{S_{C_{n-1}}}^{S_{C_n}} \lambda_u e^{-\lambda_u x} dx}. \tag{3.5}$$

It is noticed that (3.5) will be utilized for performance analysis in the next chapter. In order to consider different effects that are induced from the arrivals of the UL and the DL packets, two distinct conditions are examined: The *regular termination* is considered as the case while the sleep mode terminates at the end of the listening window. In other words, the regular termination in the nth cycle is due to the combined effects as follows: (a) there does not exist any UL or DL packets arrived in the duration of $S_{C_{n-1}}$ and $S_{D_{n-1}}$ respectively (where $S_{D_n} = \sum_{i=1}^{n} T_{D_i}$); (b) there is no UL packets that arrived during the time interval T_{C_n}; and (c) At least one DL packet has arrived within the duration of T_{D_n}. Therefore, the probability for regular termination occurring at the nth cycle (denoted as ϕ_n^R) can be computed as

$$\phi_n^{R(\mathrm{eI})} = \left(\prod_{i=1}^{n-1} e^{-\lambda_d T_{D_i}} \right) \left(1 - e^{-\lambda_d T_{D_n}}\right) \left(\prod_{i=1}^{n} e^{-\lambda_u T_{C_i}} \right). \tag{3.6}$$

On the other hand, the *interrupted termination* represents the case while the sleep mode is terminated at a time instant other than at the end of the listening window. The interrupted termination in the nth cycle can be attributed to effects as follows: (a) there does not exist either the UL or the DL packets that arrived in the time duration of $S_{C_{n-1}}$ and $S_{D_{n-1}}$ respectively; and (b) At least one UL packet has arrived during the time interval T_{C_n}. Consequently, the probability for interrupted termination (ϕ_n^I) can be obtained as

$$\phi_n^{I(\mathrm{e}^{\mathrm{I}})} = \left(\prod_{i=1}^{n-1} e^{-\lambda_d T_{D_i}}\right) \left(\prod_{i=1}^{n-1} e^{-\lambda_u T_{C_i}}\right) \left(1 - e^{-\lambda_u T_{C_n}}\right). \tag{3.7}$$

Note that it is not required to define and compute the average remaining inter-arrival time for the DL traffic, as defined in (3.5). The reason is attributed to that the DL traffic will be buffered until the beginning of the normal mode in PSC of Type I in 16e, i.e. by adopting the regular termination. Furthermore, T_{B_i} is denoted as the duration of the busy period within the normal mode as shown in Fig. 2.1(a) . It is also noted that the first busy period T_{B_0} not only contains the packets arrived in the normal mode but also includes the additional packets that were buffered before entering the normal mode. On the other hand, the parameter T_{I_i} indicates the idle duration which lies in between the busy periods.

3.1.2 Power Saving Class of Type II

The most remarkable feature of PSC of Type II in 16e is allowance of packet delivery in listening windows. Considering that η is denoted as the total number of packets acquired from both the DL in the detection window and the UL in the subsequent listening window, the probability distribution $\omega_{\eta,n}$ of η at the nth cycle can be computed as

$$\omega_{\eta,n} = \sum_{j=1}^{\eta} \frac{e^{-\lambda_d T_{D_n}}}{j!} (\lambda_d T_{D_n})^j \cdot \frac{e^{-\lambda_u T_L}}{(\eta - j)!} (\lambda_u T_L)^{\eta - j}. \tag{3.8}$$

The capacity of the listening window is denoted as the maximum number of packets (DL plus UL) that can be served within the duration T_L. The average value of capacity can be represented as $\mathcal{C} = \lfloor T_L \cdot \mu \rfloor$, where $1/\mu$ is the mean service time for both the DL and the UL packets. If η is less than or equal to the capacity $\mathcal{C}$, the data transmission will be completed in the listening window, which results in the preservation of the sleep mode. Moreover, the *regular termination* for Type II shares the same definition with Type I, however, the causes that induce this termination is considered different. The *regular termination* for Type II in the nth cycle can be attributed to the composite effects as follows: (a) there is no UL packets arrived during the time interval T_{S_k} $\forall\, k \leq n$, (b) the parameter $\eta \leq \mathcal{C}$ for all the sleep cycles less than n, and (c) the parameter $\eta > \mathcal{C}$ at the nth sleep cycle. Therefore, the probability of regular termination for PSC of Type II at the nth cycle can be redefined as

$$\phi_n^{R(\mathrm{e^{II}})} \quad = \quad \left(\prod_{i=1}^{n} e^{-\lambda_u T_{S_i}} \right) \left(\prod_{i=1}^{n-1} \pi_i \right) (1 - \pi_n) \tag{3.9}$$

where $\pi_i \triangleq \sum_{\eta=0}^{\mathcal{C}} \omega_{\eta,i}$.

On the other hand, the *interrupted termination* is redefined as the case that the sleep mode is terminated at a random time instant within the "sleep window" because of the transmission allowance during the listening window. Consequently, the interrupted termination for Type II at the nth cycle is obtained as follows: a) There is no UL packets arrived during T_{S_k} $\forall\, k \leq n-1$; b) The parameter $\eta \leq \mathcal{C}$ for all the sleep cycles less than n; and c) At least one UL packet has arrived during the time interval T_{S_n}.

Therefore, the probability for interrupted termination for PSC of Type II at the nth cycle can be expressed as

$$\phi_n^{I(\mathrm{eII})} = \left(\prod_{i=1}^{n-1} e^{-\lambda_u T_{S_i}}\right)\left(\prod_{i=1}^{n-1} \pi_i\right)\left(1 - e^{-\lambda_u T_{S_n}}\right). \tag{3.10}$$

Furthermore, the random variable $T_{u,n}$ as denoted in (3.3) should be redefined for Type II as

$$T_{u,n}^{(\mathrm{eII})} = \begin{cases} T_u & \text{if } S_{C_{n-1}} < T_u < S_{C_n} - T_L \\ 0 & \text{otherwise} \end{cases} \tag{3.11}$$

where the PDF of $T_{u,n}$ becomes

$$f_{T_{u,n}^{(\mathrm{eII})}}(t) = \begin{cases} \frac{\lambda_u e^{-\lambda_u t}}{\int_{S_{C_{n-1}}}^{S_{C_n}-T_L} \lambda_u e^{-\lambda_u x} dx} & \text{if } S_{C_{n-1}} < T_u < S_{C_n} - T_L \\ 0 & \text{otherwise.} \end{cases} \tag{3.12}$$

The average value of $T_{u,n}$ for Type II can also be computed as

$$\overline{T}_{u,n}^{(\mathrm{eII})} = \frac{\int_{S_{C_{n-1}}}^{S_{C_n}-T_L} x\lambda_u e^{-\lambda_u x} dx}{\int_{S_{C_{n-1}}}^{S_{C_n}-T_L} \lambda_u e^{-\lambda_u x} dx}. \tag{3.13}$$

3.2 Analytical Model for IEEE 802.16m

Utilizing the approach similar to the previous section, the proposed analytical model for 16m sleep mode mechanism is properly examined in the following few paragraphs.

Assuming that Poisson arrival rates of DL and UL packets are also denoted by λ_d and λ_u respectively, and $\lambda \triangleq \lambda_d + \lambda_u$. The average service rate of packet delivering equals μ. The analysis will be focused on the sleep mode operation for Type I of 16m. As for Type II, the equation $T_{C_n} = T_{C_{min}}$ should be substituted for (2.4). It is noticed that the *Analysis Period* of the proposed model represents the duration between the start of initial sleep cycle and the renewal point, as illustrated in Fig. 2.2 (The duration of normal mode is assumed to be omitted herein due to its instant occurrence compared to the whole executing time line).

As indicated in (3.3), (3.4), and (3.5), according to the remaining inter-arrival time of the UL packets in 16m ($T_u^{(\mathrm{mI})}$), the random variable $T_{u,n}^{(\mathrm{mI})}$, its PDF $f_{T_{u,n}^{(\mathrm{mI})}}(t)$, and the average value $\overline{T}_{u,n}^{(\mathrm{mI})}$ can be defined in the same way. It is noticed that herein the remaining inter-arrival time of the UL packets only owns a single value (unlike $T_r^{u,i}$ for the ith connection in 16e), owing to all the connections of the AMS are bound into a sleep cycle setting, which is so called an AMS-based scheme of 16m.

It has been mentioned in Section 2.2, UL traffic in the IEEE 16m does not affect the operation of the sleep mode. It is also specified that if the ABS receives the bandwidth request from the AMS, it shall regard that both DL and UL data transmission are allowed. In other words, during the UL transmission, the DL packets buffered at the ABS can be sent to the AMS at the same time. Note that if a DL packet arrives at the listening window of the current sleep cycle, it should wait for transmission until the next listening window, unless there is UL traffic transmitted during the period of the remaining detection window.

In order to decide whether the listening window in the renewed initial sleep cycle is extended or not, a probability factor χ_n should be defined at first based on probability distribution of the amount of issued packets, $\omega_{\eta,n}$, in (3.8). The average value of the capacity of the default listening window is also expressed as $\mathcal{C} = \lfloor T_L \cdot \mu \rfloor$. Therefore, the probability that the listening window in the renewed initial sleep cycle will not be extended is $\pi_n \triangleq \sum_{\eta=1}^{C} \omega_{\eta,n}$. On the other hand, the probability with listening window extension will be $1 - \pi_n$. The probability factor χ_n is thus defined as

$$\chi_n \triangleq \begin{cases} \pi_n & \text{not extended} \\ 1 - \pi_n & \text{extension happened.} \end{cases} \tag{3.14}$$

For fully consideration of the situations that the DL and UL traffic occur in different order, three conditions of termination of the Analysis Period are listed as follows, wherein the renewal point occurs at the end of the nth sleep cycle, i.e. the AMS receives the positive traffic indication for the sake of DL traffic coming within T_{C_n}.

3.2.1 Condition A

There is DL traffic only throughout the Analysis Period. This condition is caused by the integrated effects as follows: (a) there does not exist any UL and DL packets arrived in the duration of $S_{C_{n-1}}$ and S_{C_n} respectively (where $S_{C_n} = \sum_{i=1}^{n} T_{C_i}$), and (b) at least one DL packet arrives within the duration of T_{C_n}. The probability of Condition A can be expressed as

$$\phi_n^{A(\mathrm{m^I})} = \left(\prod_{i=1}^{n-1} e^{-\lambda_d T_{C_i}} \right) \left(1 - e^{-\lambda_d T_{C_n}} \right) \left(\prod_{i=1}^{n} e^{-\lambda_u T_{C_i}} \right) \cdot \chi_n^A \tag{3.15}$$

where $\chi_n^A = \chi_n$ in (3.14).

3.2.2 Condition B

There are DL data arriving before the the transmission of UL traffic located in the nth sleep cycle. This situation should be considered as one of the terminations of the Analysis Period, because during the UL transmission, the arrived DL packets will be served together, however, these DL data will originally make the subsequent traffic indication message become positive, that is, the occurrence of the renewal point. This condition can be attributed to the following effects: (a) there does not exist any DL packets arrived in the duration of $S_{C_{n-1}}$, (b) at least one UL packet is sent in T_{C_n}, and (c) at least one DL packet arrives before the transmission of the UL data. The probability for Condition B can be obtained as

$$\begin{aligned}\phi_n^{B(\mathrm{m^I})} &= \left(\prod_{i=1}^{n-1} e^{-\lambda_d T_{C_i}}\right)\left[1-e^{-\lambda_d (T_{u,n}-S_{C_{n-1}})}\right] \cdot \\ &\quad \left(1-e^{-\lambda_u T_{C_n}}\right)\cdot \chi_n^B. \end{aligned} \tag{3.16}$$

It is noted that χ_n^B is redefined with some modification in $\omega_{\eta,n}$ as:

$$\begin{aligned}\omega_{\eta,n}^B &\approxeq \sum_{j=1}^{\eta} \frac{e^{-\lambda_d (S_{C_n}-T_{u,n}^{(\mathrm{m^I})})}}{j!}[\lambda_d(S_{C_n}-T_{u,n}^{(\mathrm{m^I})})]^j \cdot \\ &\quad \frac{e^{-\lambda_u T_L}}{(\eta-j)!}(\lambda_u T_L)^{\eta-j}. \end{aligned} \tag{3.17}$$

Furthermore, due to the randomness of the variable $T_{u,n}^{(\mathrm{m^I})}$, average values of (3.16) and (3.17) shall be acquired as

$$\overline{\phi}_n^{B(\mathrm{m^I})} = \int_{S_{C_{n-1}}}^{S_{C_n}} \phi_n^{B\ (\mathrm{m^I})} f_{T_{u,n}^{(\mathrm{m^I})}}(t)dt \tag{3.18}$$

and

$$\overline{\omega}_{\eta,n}^B = \int_{S_{C_{n-1}}}^{S_{C_n}} \omega_{\eta,n}^B f_{T_{u,n}^{(\mathrm{m^I})}}(t)dt. \tag{3.19}$$

Accordingly, χ_n^B can be defined similarly as (3.14) using the mean value $\overline{\omega}_{\eta,n}^B$.

3.2.3 Condition C

There is at least one UL data packet arriving before the renewal point, and DL data arrive in behind. Three events are account for this condition: (a) there does not exist any DL packets arrived in the duration of $S_{C_{n-1}}$, (b) at least one UL packet is transmitted within the duration T_{C_n}, and (c) at least one DL packet occurs after the transmission of UL packets. The probability of Condition C can be computed as

$$\phi_n^{C(\mathrm{m^I})} = \left(\prod_{i=1}^{n-1} e^{-\lambda_d T_{C_i}}\right)\left(1-e^{-\lambda_u T_{C_n}}\right)\cdot \left(1-e^{-\lambda_d (S_{C_n}-T_{u,n}^{(\mathrm{m^I})})}\right)\cdot \chi_n^C \quad (3.20)$$

At the same time, the presentation of χ_n^C needs some modification in $\omega_{\eta,n}$:

$$\omega_{\eta,n}^C = \sum_{j=1}^{\eta} \frac{e^{-\lambda_d T_{C_n}^*}}{j!}(\lambda_d T_{C_n}^*)^j \cdot \frac{e^{-\lambda_u T_L}}{(\eta-j)!}(\lambda_u T_L)^{\eta-j} \quad (3.21)$$

where $T_{C_n}^* = S_{C_n} - T_{u,n}^{(\mathrm{m^I})} - E[T_n^{u\_trans}]$, and the term $E[T_n^{u\_trans}]$ denotes the mean time duration utilized to UL transmission in the nth sleep cycle, i.e. $E[T_n^{u\_trans}] = \frac{1}{\mu}\sum_{i=0}^{\infty} i\cdot \frac{e^{-\lambda_u T_{C_n}}(\lambda_u T_{C_n})^i}{i!}$. The mean value of $\omega_{\eta,n}^C$ is obtained by the same way in (3.19). Consequently, χ_n^C can be expressed as (3.14) by applying $\overline{\omega}_{\eta,n}^C$ as well.

These probabilities of conditions will be used for the performance evaluation in the next chapter.

Chapter 4

Performance Analysis of IEEE 802.16e/m Systems

In this chapter, two performance metrics, the sleep ratio and mean waiting time, are discussed in the following two sections. Both the 16e and 16m systems are investigated in accordance with the two metrics.

4.1 Sleep Ratio

4.1.1 As for IEEE 802.16e

In this subsection, the sleep ratio $\mathcal{R}$ of 16e is defined as the ratio of the average sleep time to the average Analysis Period, i.e.[1]

$$\mathcal{R}^{(\mathrm{e})} \triangleq \frac{E[T_S^{*\ (\mathrm{e})}]}{E[T_S^{(\mathrm{e})}] + E[T_N]} \tag{4.1}$$

[1]It is noticed that the superscript $(\mathrm{e}^{\mathrm{I}})$ and $(\mathrm{e}^{\mathrm{II}})$ are simplified to (e), which indicates it is suitable for PSC of Type I and Type II for 16e, i.e., both Type I and II share the common expression. For example, (4.2) is a simplified form of $E[T_S^{(\mathrm{e}^{\mathrm{I}})}] = \sum_{n=1}^{\infty}(\phi_n^{R(\mathrm{e}^{\mathrm{I}})} \cdot S_{C_n} + \phi_n^{I(\mathrm{e}^{\mathrm{I}})} \cdot \overline{T}_{u,n}^{(\mathrm{e}^{\mathrm{I}})})$ and $E[T_S^{(\mathrm{e}^{\mathrm{II}})}] = \sum_{n=1}^{\infty}(\phi_n^{R(\mathrm{e}^{\mathrm{II}})} \cdot S_{C_n} + \phi_n^{I(\mathrm{e}^{\mathrm{II}})} \cdot \overline{T}_{u,n}^{(\mathrm{e}^{\mathrm{II}})})$.

where $T_S^{(\mathrm{e})}$ and T_N represent the lengths of the sleep mode and the normal mode of 16e as shown in Fig. 2.1. The parameter $T_S^{*\ (\mathrm{e})}$ in (4.1) is the length of sleep mode excluding total involved listening windows, i.e. the summation of the pure sleep windows. The mean value of $T_S^{(\mathrm{e})}$ can be calculated according to conditional probabilities of both the normal and the interrupted terminations as

$$\begin{aligned} E[T_S^{(\mathrm{e})}] &= E[T_S^{(\mathrm{e})}|\text{regular termination}] \\ &\quad + E[T_S^{(\mathrm{e})}|\text{interrupted termination}] \\ &= \sum_{n=1}^{\infty}(\phi_n^{R\ (\mathrm{e})} \cdot S_{C_n} + \phi_n^{I\ (\mathrm{e})} \cdot \overline{T}_{u,n}^{(\mathrm{e})}) \end{aligned} \tag{4.2}$$

Considering that δ is denoted as the δth sleep cycle where $E[T_S^{(\mathrm{e})}]$ exists, i.e.

$$\delta = \max\left\{n : \sum_{i=1}^{n} T_{C_i} < E[T_S^{(\mathrm{e})}]\right\} + 1. \tag{4.3}$$

Therefore, $E[T_S^{*\ (\mathrm{e})}]$ can be acquired as

$$E[T_S^{*\ (\mathrm{e})}] = \sum_{i=1}^{\delta-1} T_{S_i^{(\mathrm{e})}} + \min\left\{(E[T_S^{(\mathrm{e})}] - S_{C_{\delta-1}}), T_{S_\delta^{(\mathrm{e})}}\right\} \tag{4.4}$$

On the other hand, the expected value of T_N can be obtained by referring from [20] as

$$E[T_N] = E[T_{B_0}] + \kappa \cdot (E[T_{I_i}] + E[T_{B_{i\neq 0}}]) \tag{4.5}$$

where the meanings of T_{B_0}, $T_{B_{i\neq 0}}$, and T_{I_i} have been explained in Section 3.1.1. The parameter κ is denoted as the average number of alternated cycles before the idle period has reached the timeout value τ, which is determined as $\kappa = \sum_{i=0}^{\infty} i \cdot (1 - P_\tau)^i \cdot P_\tau = (1/P_\tau) - 1$ where $P_\tau = e^{-\lambda\tau}$. By adopting the M/G/1 queueing model without vacation as in [21], both $E[T_{B_{i\neq 0}}]$ and $E[T_{I_i}]$ can be obtained as

$$E[T_{B_{i\neq 0}}] = \frac{1}{\mu - \lambda} \quad (4.6)$$

$$E[T_{I_i}] = \frac{1}{\lambda}. \quad (4.7)$$

Assuming that the probability of i packets coming before the beginning of the normal mode is denoted as φ_i, the mean value of the first busy period can be computed by extending the concept from [22] as

$$E[T_{B_0}] = \sum_{i=1}^{\infty}(i \cdot E[T_{B_i}]) \cdot \varphi_i \quad (4.8)$$

It is noticed that φ_i is the only remaining parameter that is required to be determined in order to complete the modeling of the sleep ratio of 16e. The computation of φ_i will be separately discussed for Type I and Type II as follows.

4.1.1.1 Type I

The parameter $\varphi_i^{(\mathrm{e^I})}$ will be acquired based on both the regular and the interrupted terminations. For regular termination at the nth cycle, the probability of i packets that are initiated before the start of the normal mode can be represented as

$$\varphi_{i,n}^{R(\mathrm{e^I})} = \frac{\Phi_{i,n}^{R(\mathrm{e^I})}}{1 - \Phi_{0,n}^{R(\mathrm{e^I})}} \quad (4.9)$$

with $i \geq 1$. $\Phi_{i,n}^{R(\mathrm{e^I})}$ is the probability of i DL packets in both the nth detection window and the next listening window as

$$\Phi_{i,n}^{R(\mathrm{e^I})} = \frac{e^{-\lambda_d(T_{D_n}+T_L)}}{i!}[\lambda_d(T_{D_n} + T_L)]^i. \quad (4.10)$$

On the other hand, for the interrupted termination case at the nth cycle, the probability of i packets (DL plus UL) before the initiation of the normal mode is acquired as

$$\varphi_{i,n}^{I(\mathrm{e^{II}})} = \Phi_{i-1,n}^{I(\mathrm{e^{II}})} \tag{4.11}$$

with $i \geq 1$. $\Phi_{i,n}^{I(\mathrm{e^{II}})}$ is the probability of i DL packets arrived before the start of the interrupted termination at the nth cycle as

$$\Phi_{i,n}^{I(\mathrm{e^{I}})} = \frac{e^{-\lambda_d(T_{u,n}^{(\mathrm{e^{II}})} - S_{D_{n-1}})}}{i!} \left[\lambda_d(T_{u,n}^{(\mathrm{e^{II}})} - S_{D_{n-1}})\right]^i \tag{4.12}$$

Due to the randomness of the variable $T_{u,n}^{(\mathrm{e^{II}})}$, the mean value of (4.11) is acquired as

$$\overline{\varphi}_{i,n}^{I(\mathrm{e^{II}})} = \int_{S_{C_{n-1}}}^{S_{C_n}} \varphi_{i,n}^{I(\mathrm{e^{II}})} f_{T_{u,n}}^{(\mathrm{e^{II}})}(t)dt. \tag{4.13}$$

As a result, $\varphi_i^{(\mathrm{e^{II}})}$ can be derived by combining (3.6), (3.7), (4.9), and (4.13) as

$$\varphi_i^{(\mathrm{e^{II}})} = \sum_{n=1}^{\infty} \varphi_{i,n}^{R(\mathrm{e^{II}})} \phi_n^{R(\mathrm{e^{II}})} + \overline{\varphi}_{i,n}^{I(\mathrm{e^{II}})} \phi_n^{I(\mathrm{e^{II}})}. \tag{4.14}$$

4.1.1.2 Type II

Similar to the above discussion, both the regular and the interrupted termination cases are considered for the PSC of Type II in 16e. For regular termination, a portion of the data packets will be transmitted within the listening window; while the remaining packets will be delivered by starting the normal mode at the end of the listening window. Therefore, the probability of i packets initiated before the start of the normal mode is acquired as

$$\varphi_{i,n}^{R(\mathrm{e^{II}})} = \frac{\omega_{(i+\mathcal{C}),n}}{1 - \sum_{j=0}^{\mathcal{C}} \omega_{j,n}} \tag{4.15}$$

with $i \geq 1$, where $\omega_{(j,n}$ is same as (3.8). For interrupted termination, the probability $\varphi_{i,n}^{I(\text{II})}$ becomes

$$\varphi_{i,n}^{I(\text{e}^{\text{II}})} = \Phi_{i-1,n}^{I(\text{e}^{\text{II}})} \quad \text{with } i \geq 1 \tag{4.16}$$

$$\Phi_{i,n}^{I(\text{e}^{\text{II}})} = \frac{e^{-\lambda_d(T_{u,n}^{(\text{e}^{\text{II}})} - S_{D_{n-1}})}}{i!} \left[\lambda_d(T_{u,n}^{(\text{e}^{\text{II}})} - S_{D_{n-1}})\right]^i. \tag{4.17}$$

The mean value of $\varphi_{i,n}^{I(\text{II})}$ can also be obtained as

$$\overline{\varphi}_{i,n}^{I(\text{e}^{\text{II}})} = \int_{S_{C_{n-1}}}^{S_{C_n} - T_L} \varphi_{i,n}^{I(\text{e}^{\text{II}})} f_{T_{u,n}}^{(\text{e}^{\text{II}})}(t)dt. \tag{4.18}$$

Consequently, $\varphi_i^{(\text{II})}$ is computed by combining (3.9), (3.10), (4.15), and (4.18) as

$$\varphi_i^{(\text{e}^{\text{II}})} = \sum_{n=1}^{\infty} \varphi_{i,n}^{R(\text{e}^{\text{II}})} \phi_n^{R(\text{e}^{\text{II}})} + \overline{\varphi}_{i,n}^{I(\text{e}^{\text{II}})} \phi_n^{I(\text{e}^{\text{II}})}. \tag{4.19}$$

4.1.2 As for IEEE 802.16m

On account of the continuous proceeding of sleep mode in 16m, the sleep ratio $\mathcal{R}$ needs to be redefined as

$$\mathcal{R}^{(\text{m})} \triangleq \frac{E[T_S^{*\ (\text{m})}]}{E[T_S^{(\text{m})}] + E[T_{UL}]} \tag{4.20}$$

where $T_S^{(\text{m})}$ is the length of the summation of sleep cycles within the Analysis Period, and T_{UL} indicates the additional time duration used for UL data transmission. The term $T_S^{*\ (\text{m})}$ also denotes the amount of pure sleep windows, i.e., the length of the Analysis Period excluding any awake state, such as the listening windows and the transmission of UL traffic. The average value of $T_S^{*\ (\text{m})}$ can be obtained by conditional probabilities of the aforementioned three conditions:

$$\begin{aligned} E[T_S^{*\ (\mathrm{m})}] &= E[T_S^{*\ (\mathrm{m})}|\text{Condition A}] + E[T_S^{*\ (\mathrm{m})}|\text{Condition B}] + \\ &\quad E[T_S^{*\ (\mathrm{m})}|\text{Condition C}] \\ &= \sum_{n=1}^{\infty}\{(\phi_n^{A(\mathrm{m})} + \overline{\phi}_n^{B(\mathrm{m})} + \overline{\phi}_n^{C(\mathrm{m})})\left(\sum_{i=1}^{n} T_{S_i}\right) \\ &\quad +\phi_n^{A\_ext(\mathrm{m})}\left[\sum_{i=2}^{n} T_{S_i} + (T_{C_{min}} - T_{L_{ext}^A})\right] \\ &\quad +\overline{\phi}_n^{B\_ext(\mathrm{m})}\left[\sum_{i=2}^{n} T_{S_i} + (T_{C_{min}} - T_{L_{ext}^B})\right] \\ &\quad +\overline{\phi}_n^{C\_ext(\mathrm{m})}\left[\sum_{i=2}^{n} T_{S_i} + (T_{C_{min}} - T_{L_{ext}^C})\right]\} \end{aligned} \tag{4.21}$$

where $\phi_n^{k\_ext(\mathrm{m})}$ represents $\phi_n^{k(\mathrm{m})}$ with $\chi_n^k = 1-\pi_n$ are substituted, $k \in A, B, C$. Moreover, the length of extended listening windows can be obtained by following the notion of (4.5) as

$$T_{L_{ext}} = \sum_{i=1}^{\infty} i \cdot \left(\frac{1}{\mu - \lambda}\right) \cdot \Omega_i \tag{4.22}$$

with Ω_i equals to $\varphi_{i,n}^{R(\mathrm{e^{II}})}$ in (4.15). It is noted that the superscript k of $T_{L_{ext}^k}$ in (4.21), the corresponding $\omega_{\eta,n}^k$, $k \in A, B, C$ should be exploited.

Suppose that δ^* is regarded as the average δ^*th sleep cycle where $E[T_S^{*\ (\mathrm{m})}]$ is located, that is,

$$\delta^* = \min\left\{n : \sum_{i=1}^{n} T_{S_i} > E[T_S^{*\ (\mathrm{m})}]\right\}. \tag{4.23}$$

Consequently, the remaining parameters in (4.20) can be determined as

$$\begin{aligned} E[T_{UL}] &= \frac{E[\text{Number of occured UL packets}]}{\mu} \\ &= \frac{1}{\mu}\sum_{i=0}^{\infty} i \cdot \frac{e^{-\lambda_u E[T_S^{(\mathrm{m})}]}(\lambda_u E[T_S^{(\mathrm{m})}])^i}{i!} \end{aligned} \tag{4.24}$$

where $E[T_S^{(\mathrm{m})}] = \sum_{i=1}^{\delta^*} T_{C_i}$.

4.2 Mean Packet Delay

Considering that the serving policy of the BS in 16e or the ABS in 16m is first-come-first-serve (FCFS) and the M/G/1 queueing system is adopted, the average packet delay is evaluated as follows.

4.2.1 As for IEEE 802.16e

The mean waiting time of a packet in 16e is defined by including both the queueing time and the service time as

$$\begin{aligned} E[W^{(\mathrm{e})}] =& E[W_{B_0}]P_{B_0} + U(E[W_{L_1}]P_{L_1} + E[W_{L_{i\neq1}}]P_{L_{i\neq1}}) \\ &+ E[W_{B_{i\neq0}}](1 - P_{B_0} - U(P_{L_1} + P_{L_{i\neq1}})) \end{aligned} \tag{4.25}$$

where $U = 0$ for PSC of Type I and $U = 1$ for Type II. W_{B_i} is the waiting time in the ith busy period with probability P_{B_i}. W_{L_i} represents the waiting time in the listening window with its probability P_{L_i} while Type II is considered. According to the Pollaczek-Khintchine mean value formula of M/G/1 queueing system as in [21], $E[W_{B_{i\neq0}}]$ can be obtained as

$$E[W_{B_{i\neq0}}] = \frac{\rho}{\lambda} + \frac{\rho^2 + \lambda^2\sigma^2}{2\lambda(1-\rho)} \tag{4.26}$$

where σ^2 is the variance of the service time and $\rho = \lambda/\mu$ stands for the traffic intensity. Moreover, based on the M/G/1 queueing system with multiple vacations [23], the mean waiting time in the first busy period can be calculated as

$$E[W_{B_0}] = E[W_{B_{i\neq 0}}] + E[T_V]. \tag{4.27}$$

The parameter T_V is the remaining vacation time, which can be expressed as (4.28) because of the average sleep cycle δ.

$$\begin{aligned} E[T_V] =& \frac{T_{D_\delta} + T_L}{2} \cdot P_R \\ &+ (1 - P_R)(1 - \Phi_{0,\delta}^{I(\mathrm{e})}) \cdot \frac{\overline{T}_{u,\delta}^{(\mathrm{e})} - S_{C_{\delta-1}}}{2} \end{aligned} \tag{4.28}$$

where $P_R = (\phi_\delta^{R(\mathrm{e})})/(\phi_\delta^{R(\mathrm{e})} + \phi_\delta^{I(\mathrm{e})})$. The remaining terms within (4.25) will be computed for both Type I and Type II below.

4.2.1.1 Type I

The only parameter that is left to be determined for Type I is the probability of the average number of packets initiated in the first busy period, i.e.

$$P_{B_0} = \frac{\varphi^{(\mathrm{e^I})} + \lambda \cdot E[T_{B_0}]}{\lambda \cdot E[T_N] + \varphi^{(\mathrm{e^I})}} \tag{4.29}$$

where $\varphi^{(\mathrm{e^I})} = \sum_{i=1}^{\infty} i \cdot \varphi_i^{(\mathrm{e^I})}$ represents the average number of packets happened at the start of the normal mode.

4.2.1.2 Type II

Considering $\nu_{i,n}$ is denoted as the probability of i DL packets at the nth detection window under the condition that the sleep mode terminates after the nth cycle. The parameter $\nu_{i,n}$ can be obtained as

$$\nu_{i,n} = \frac{e^{-\lambda_d T_{D_n}}}{i!}(\lambda_d T_{D_n})^i \cdot \left(\sum_{j=0}^{\mathcal{C}-i} \frac{e^{-\lambda_u T_L}}{j!}(\lambda_u T_L)^j\right) \cdot \frac{1}{\pi_n}. \tag{4.30}$$

Its expected value in terms of i can be computed as

$$\nu_n = \sum_{i=0}^{\mathcal{C}} i \cdot \nu_{i,n}. \tag{4.31}$$

Moreover, according to the M/G/1 queueing system with multiple vacations, the mean waiting time in the listening window can be approximated as

$$E[W_{L_i}] \approxeq \frac{T_{D_i}}{2} + \frac{\nu_i}{2} \cdot \frac{1}{\mu}. \tag{4.32}$$

It is noted that the waiting time from the UL packets happened within the listening window is ignorable considering the comparably smaller time duration of the listening window. Consequently, the other parameters within (4.25) for Type II of 16e can be calculated as follows according to the average sleep cycle δ.

$$P_{B_0} = \frac{\lambda \cdot E[T_{B_0}] + \varphi^{(\mathrm{eII})}}{\lambda \cdot E[T_N] + \varphi^{(\mathrm{eII})} + \nu_1 + \nu \cdot (\delta - 1)} \tag{4.33}$$

$$P_{L_1} = \frac{\nu_1}{\lambda \cdot E[T_N] + \varphi^{(\mathrm{eII})} + \nu_1 + \nu \cdot (\delta - 1)} \tag{4.34}$$

$$P_{L_{i\neq 1}} = \frac{\nu \cdot (\delta - 1)}{\lambda \cdot E[T_N] + \varphi^{(\mathrm{II})} + \nu_1 + \nu \cdot (\delta - 1)} \tag{4.35}$$

where $\varphi^{(\mathrm{eII})} = \sum_{i=1}^{\infty} i \cdot \varphi_i^{(\mathrm{eII})}$ and $\nu = \nu_{i\neq 1}$ since the value of $\nu_{i\neq 1}$ are the same for all $i \neq 1$.

4.2.2 As for IEEE 802.16m

On the other hand, the average packet delay for 16m can be computed as the sum of the wait time for serving in the listening window and the time spent by the UL packets within the additional duration of the UL transmission, i.e. $E[W^{(\mathrm{m})}] = E[W_L] + E[W_{UL}]$

Similarly, $E[W_L]$ can be further expressed as

$$E[W_L] = E[W_{M/G/1}] + E[T_V] \tag{4.36}$$

where $E[W_{M/G/1}]$ is the waiting time of a normal M/G/1 queuing system, which is equal to (4.26). Also,

$$E[W_{UL}] = \frac{1}{\mu} + \frac{(\lambda_u/\mu)^2 + \lambda_u^2\sigma^2}{2\lambda_u(1-\lambda_u/\mu)}. \tag{4.37}$$

Furthermore, T_V is the remaining vacation time of the system and its average value would be

$$E[T_V] = \frac{T_{C_{\delta^*}}}{2}\cdot P_A + \frac{(\overline{T}^{(\mathrm{m})}_{u,\delta^*} - S_{C_{\delta^*-1}})}{2}\cdot P_B + \frac{T_{C^*_{\delta^*}}}{2}\cdot P_C \tag{4.38}$$

according to the average sleep cycle δ^*. Moreover, $P_k = \Phi^k_{\delta^*}/(\Phi^A_{\delta^*} + \Phi^B_{\delta^*} + \Phi^C_{\delta^*})$, where $\Phi^k_{\delta^*} = \phi^{k(\mathrm{m})}_{\delta^*} + \phi^{k\_ext(\mathrm{m})}_{\delta^*}$, $k \in A, B, C$ (mean values of $\phi^{k(\mathrm{m})}_{\delta^*}$ and $\phi^{k\_ext(\mathrm{m})}_{\delta^*}$ shall be utilized for $k = B, C$).

Chapter 5

Proposed POMDP-based Sleep Window Determination (PSWD) Approach

According to the performance analysis, it is intuitively observed that the 16m seems to be more power efficient than that of 16e. However, there are numbers of redundant under-utilized listening windows in the sleep mode operation of 16m owing to the scheme of binary-exponential growth of sleep cycles adopted by 16m. Moreover, it is also responsible for excessive energy cost during state transition, i.e., switching from sleep

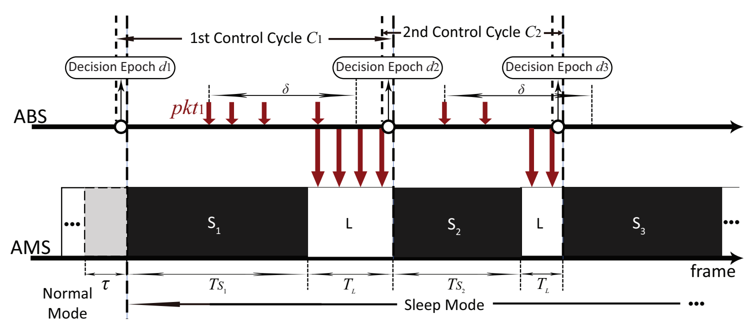

Figure 5.1: Schematic diagram of ideal sleep mode operation for an AMS.

windows to listening windows and vice versa. It is thus motivated that a more flexible sleep mode mechanism, i.e., a sleep windows decision approach should be designed which adaptively adjusts the length of sleep windows based on the traffic state. In [24] recently published, a statistical sleep window control (SSWC) approach has been proposed for the sleep windows decision problem under tolerable average packet delay for non-real-time DL traffic, that is, Type I in 16m. In this work, the design concept is further extended in order to be fulfilled for all traffic patterns and power-saving types in 16m, including both Type I and Type II. Furthermore, both the DL and UL traffic are also considered during the selection of sleep windows sizes. First of all, the definition of *control cycles* for the PSWD approach is stated as follows.

Definition 1 (Control Cycle). *Given an ABS and an AMS 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* S_i*, and a listening window* L_i*. The ABS determines the length of the sleep window* S_i *at the decision epoch* d_i*. The AMS stays in the power-saving mode during the sleep window with length* T_{S_i} *and wakes up for data transmission in the listening window* L_i *until finishing serving all packets, then enters the subsequent control cycle.*

Fig. 5.1 illustrates the ideal sleep mode operation of a 16m AMS which the proposed PSWD approach intends to achieve, wherein all the control signals are omitted for the sake of description convenience. Each control cycle C_i ($i \neq 1$) is overlapped with the adjacent control cycles C_{i-1} and C_{i+1}. The first control cycle C_1 begins at the last frame of AMS's idle period in the normal mode. The remainder control cycles are individually started at the end of every listening window within the previous control cycle.

The target of PSWD approach is to find adequate length of sleep window in each control cycle in light of present traffic state, which meets the delay constraint of packets and maximizes the power-saving efficiency as possible. According to the process of ongoing sleep mode parameter update mentioned in Section 2.3, in the proposed PSWD approach, the ABS can inform an AMS about the calculated length of each sleep window without any additional control overhead by using originally defined messages, such as AAI_SLP-RSP or AAI_TRF-IND. On the contrary, an AMS may also send its UL traffic condition through AAI_SLP-REQ in order to provide the reference UL information to the serving ABS. It is noted that by means of exploiting such parameter negotiation scheme, each sleep window in every control cycle belongs to a brand-new initial sleep cycle, hence the proposed PSWD approach can be applied to no matter Type I or Type II of 16m.

As shown in Fig. 5.1, the calculated length of sleep window should meet the tolerable delay, e.g. for the first sleep window S_1, it shall be terminated before the expiration of the first coming packet pkt_1, that is, the termination selected at the decision epoch d_1 has to fall within the range δ. Consequently, it is inferred that the determined length of each sleep window is dominated by the knowledge of the current traffic patterns, especially DL traffic in 16m, for the interruption resulted from UL transmission at any time may have no impact on the length and phase of the sleep cycles. Nevertheless, these kinds of traffic states are considered difficult to be acquired directly. Only the number of packets arrived in the buffer during the previous control cycle can be observed, which may provide sufficient information for the ABS to estimate the potential state of present traffic.

For the situation described above, a POMDP [25] [26] technique is fairly feasible for the ABS to speculate about the present state of traffic at each decision epoch by the observed information from the buffers. In the following three sections, details of the proposed PSWD method will be introduced, which consist of the estimation procedure for current traffic state by the POMDP scheme, the evaluation metrics, and the sleep window determination policy of PSWD approach.

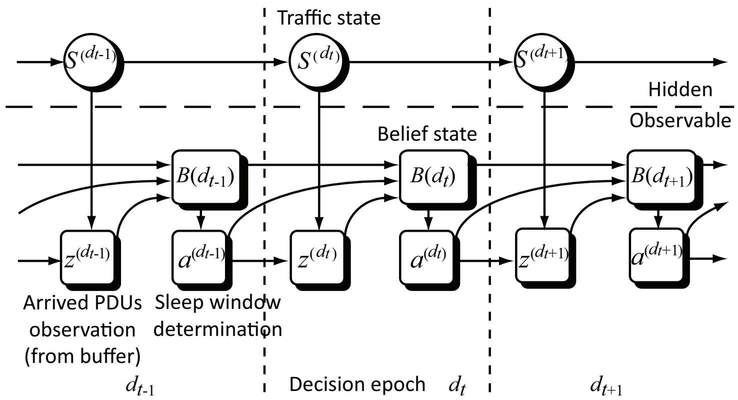

Figure 5.2: Schematic diagram of POMDP model for PSWD approach

5.1 Traffic State Estimation

The procedure of traffic state estimation resorts to a POMDP model in order to conjecture the present traffic state at each decision epoch. A typical POMDP model can be expressed by 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. In the proposed PSWD approach, the source of DL and UL traffic are generated by a discrete-time Markov-modulated Poisson process (dMMPP), which is considered more general than the conventional Poisson traffic, and can be capable of capturing the correlation characteristics in the modern Internet and multimedia traffic at multiple time scales [27] [28] [29]. Here $\mathcal{S}$ consists of two components: $\mathcal{S}_d$ and $\mathcal{S}_u$ which correspond to the set of dMMPP states of DL and UL traffic, respectively. Also, $\{\mathcal{T}_d, \mathcal{T}_u\} \in \mathcal{T}$ are related to the state transition probability matrixes of DL/UL direction. Furthermore, the set of actions is defined as $\mathcal{A} = \{a_1, a_2, \cdots, a_N\}$ where a_n represents the action of selecting a sleep window of length $T_{S_{a_n}}$ corresponding to the outputs of the PSWD approach.

Considering a sequence of control cycle $\{C_1, C_2, \cdots, C_T\}$ in the proposed SSWC approach, the set of corresponding decision epoches is defined as $\mathcal{D} = \{d_1, d_2, \cdots, d_T\}$.

Fig. 5.2 depicts the schematic diagram of the POMDP model for the proposed PSWD approach (as for DL traffic). At each decision epoch $d_t \in \mathcal{D}$, the traffic state $s_d^{(d_t)}$ or $s_u^{(d_t)} \in \mathcal{S}$ is considered hidden and unobservable. However, the number of packets that arrived in the buffer of ABS/AMS during the previous control cycle C_{t-1} is available and can be acquired. Thus the set of observations on the quantity of arrivals is written as $\mathcal{Z}_d = \{z_d^{(d_1)}, z_d^{(d_2)}, \cdots, z_d^{(d_T)}\}$ where $z_d^{(d_i)}$ denotes the number of DL packets arrived at the ABS in the interval between the $(i-1)$th and the ith decision epoches, and $\mathcal{Z}_u$ can also be defined in this way. The observation probability of DL packets can be defined as

$$\begin{aligned} o(z_d^{(d_t)}, a^{(d_{t-1})}, s_d^{(d_t)}) &\triangleq Pr(z_d^{(d_t)}|a^{(d_{t-1})}, s_d^{(d_t)}) \\ &= \frac{(\lambda_d^{(d_t)} T_{S_{a^{(d_{t-1})}}})^{z_d^{(d_t)}}}{z_d^{(d_t)}!} e^{-(\lambda_d^{(d_t)} T_{S_{a^{(d_{t-1})}}})}, \end{aligned} \tag{5.1}$$

which is a conditional probability of an observation $z_d^{(d_t)} \in \mathcal{Z}$ at decision epoch d_t given the action (i.e. length of previous sleep window) $a^{(d_{t-1})} \in \mathcal{A}$ chosen at d_{t-1} and the present DL traffic state $s_d^{(d_t)} \in \mathcal{S}$ at d_t, in which arrival rate equals $\lambda_d^{(d_t)}$.

In order to nearly achieve the optimal results, the notion of *belief state* is introduced in the POMDP model by referring to the recent history of previous observations so as to estimate the present traffic state more precisely than merely by utilizing most recent observations from the buffer. Given a decision epoch $d_t \in \mathcal{D}$, the set of belief state of DL traffic is defined as $\mathcal{B}_d(d_t) = \{b(s_{d\_1}^{(d_t)}), b(s_{d\_2}^{(d_t)}), \cdots, b(s_{d\_M}^{(d_t)})\}$, which represents the estimated probability distribution over the set of traffic states $\mathcal{S} = \{s_{d\_1}, s_{d\_2}, \cdots, s_{d\_M}\}$. Each element $b(s_{d\_j}^{(d_t)})$ denotes the probability of DL traffic state s_{d_j} at decision epoch d_t. It is noted that $0 \le b(s_{d\_j}^{(d_t)}) \le 1, \forall s_{d\_j} \in \mathcal{S}_d$ and $\sum_{\forall s_{d\_j}} b(s_{d\_j}^{(d_t)}) = 1, \forall d_t \in \mathcal{D}$ since the DL traffic must belong to one of the states within the $\mathcal{S}_d$ set at any given decision epoch. As shown in Fig. 5.2, the belief state $\mathcal{B}_d(d_t)$ is updated at decision epoch d_t

by exploiting previous action $a^{(d_t)} \in \mathcal{A}$ and the corresponding observation $z_d^{(d_{t+1})} \in \mathcal{Z}$. Thus each element $b(s_{d\_j}^{(d_t)})$ of the belief state $\mathcal{B}_d(d_{t+1})$ can be derived as [1]

$$
\begin{aligned}
b(s_{d\_j}^{(d_t)}) &= Pr(s_{d\_j}^{(d_t)} | \mathcal{B}_d(d_{t-1}), a^{(d_{t-1})}, z_d^{(d_t)}) && (5.2)\\
&= \frac{Pr(z_d^{(d_t)} | a^{(d_{t-1})}, s_{d\_j}^{(d_t)}, \mathcal{B}_d(d_{t-1})) Pr(s_{d\_j}^{(d_t)} | a^{(d_{t-1})}, \mathcal{B}_d(d_{t-1}))}{Pr(z_d^{(d_t)} | a^{(d_{t-1})}, \mathcal{B}_d(d_{t-1}))} && (5.3)\\
&= \frac{o(z_d^{(d_t)}, a^{(d_{t-1})}, s_{d\_j}^{(d_t)}) \sum_{s_{d\_i}^{(d_t-1)} \in \mathcal{S}_d} p_{i,j} b(s_{d\_i}^{(d_t-1)})}{\sum_{s_{d\_i}^{(d_t-1)} \in \mathcal{S}_d} \sum_{s_{d\_j}^{(d_t)} \in \mathcal{S}_d} b(s_{d\_i}^{(d_t-1)}) p_{i,j} o(z_d^{(d_t)}, a_{(d_{t-1})}, s_{d\_j}^{(d_t)})}. && (5.4)
\end{aligned}
$$

It is noted that the belief state is a integrated statistics for the entire history of the process, which progressively merges the effect of previously determined action and the corresponding observation at each decision epoch. Since the belief state is updated at each decision epoch, the time complexity can be calculated as $O(|\mathcal{S}|)$, where $|\mathcal{S}|$ represents the total number of states in $\mathcal{S}$, including both DL and UL traffic. By means of the belief state, more precise traffic states can be appraised via exploiting the proposed PSWD approach.

5.2 Evaluation Metrics

Since the proposed PSWD approach intends to determine the appropriate action, i.e. selection of the length of each sleep window based on the estimated traffic state, the performance should be evaluated first by a variety of state/action pair. Owing to frequent state transition in 16m between sleep windows and listening windows, two performance metrics, average energy cost and mean packet delay, are investigated in order to manifest the improvement in the PSWD approach by taking the power consumption of state

[1] For UL traffic, the observation probability and the belief state can be derived in the same way as (5.1) and (5.2) by substituting $\lambda_u^{(d_t)}$, $z_u^{(d_t)}$, and $s_u^{(d_t)} \in \mathcal{S}_u$ instead.

switching into consideration. The evaluation metrics corresponding to each state/action pair (s_{d_i}, s_{u_k}, a_n), $\forall s_{d\_i} \in \mathcal{S}_d$, $\forall s_{u\_k} \in \mathcal{S}_u$ and $\forall a_n \in \mathcal{A}$, are described as follows.

5.2.1 Average Energy Cost

To evaluate the power consumption of an AMS in the sleep mode, the *energy cost* is defined as the average energy consumption per frame during a control cycle. Let ε_S and ε_B denote the energy consumption per frame within the sleep window and busy frame in each listening window, respectively. Moreover, the energy consumption of switching between listening windows and sleep windows is considered as ε_{SW}. The average energy cost of the (s_{d_i}, s_{u_k}, a_n) pair can be expressed as

$$\begin{aligned}\overline{E}(s_{d\_i}, s_{u\_k}, a_n) =& \{2\varepsilon_{SW} + \varepsilon_S E[T_S(s_{d\_i}, s_{u\_k}, a_n)] + \varepsilon_B E[T_L(s_{d\_i}, s_{u\_k}, a_n)] \\ &+ (1 - e^{-\lambda_{u\_k} T_{S_{a_n}}})(2\varepsilon_{SW} + \varepsilon_B E[T_{UL}(s_{d\_i}, s_{u\_k}, a_n)])\} \\ &/\{E[T_S(s_{d\_i}, s_{u\_k}, a_n)] + E[T_L(s_{d\_i}, s_{u\_k}, a_n)] + E[T_{UL}(s_{d\_i}, s_{u\_k}, a_n)]\},\end{aligned} \tag{5.5}$$

wherein $E[T_S(s_{d\_i}, s_{u\_k}, a_n)]$ and $E[T_L(s_{d\_i}, s_{u\_k}, a_n)]$ represent the expected length of the sleep window and the following listening window, respectively. Since the action a_n is determined according the state (s_{d_i}, s_{u_k}), $E[T_S(s_{d\_i}, s_{u\_k}, a_n)]$ is intuitively equal to $T_{S_{a_n}}$; while $E[T_L(s_{d\_i}, s_{u\_k}, a_n)]$ can be derived by applying the Little's theorem [21] as

$$E[T_L(s_{d\_i}, s_{u\_k}, a_n)] = \frac{\lambda_{d\_i} T_{S_{a_n}}}{\mu - \lambda_{d\_i}}. \tag{5.6}$$

Furthermore, $E[T_{UL}(s_{d\_i}, s_{u\_k}, a_n)]$ denotes the average length of additional duration utilized for UL packets transportation in each control cycle, which is expressed as

$$E[T_{UL}(s_{d\_i}, s_{u\_k}, a_n)]) = \frac{\lambda_{u\_k}}{\mu}\left(E[T_S(s_{d\_i}, s_{u\_k}, a_n)] + E[T_L(s_{d\_i}, s_{u\_k}, a_n)]\right). \qquad (5.7)$$

5.2.2 Mean Packet Delay

The *packet delay* can be acquired by the aforementioned process of 16e/m analysis. Since the packet arrival follows the Poisson distribution in each state $\in \mathcal{S}$ and the service rate is also assumed as general distribution, a $dMMMP/G/1$ queueing model (that is, an $M/G/1$ queueing model for each individual state) with server vacation is utilized to describe the packet arrival and departure. The expected packet delay of the (s_{d_i}, s_{u_k}, a_n) pair can be expressed as

$$\begin{aligned}\overline{D}(s_{d\_i}, s_{u\_k}, a_n) =& E[T_V(s_{d\_i}, s_{u\_k}, a_n)] + E[W_{M/G/1}] \\ &+ (1 - e^{-\lambda_{u\_k} T_{S_{a_n}}})\left(-E[T_V(s_{d\_i}, s_{u\_k}, a_n)]/2 + E[W_{UL}]\right)\end{aligned} \qquad (5.8)$$

where $E[T_V(s_{d\_i}, s_{u\_k}, a_n)]$ stands for the average remaining length of sleep window (remaining vacation time) for arriving packets, which equals to $T_{S_{a_n}}/2$; while $E[W_{M/G/1}]$ and $E[W_{UL}]$ can be obtained directly from (4.26) and (4.37) by substituting λ_{d_i} and λ_{u_k}, respectively. It is noted the negative term of (5.8) means the allowance of delivery for some buffered DL packets during UL transmission which averagely decrease half the remaining vacation time of total packets.

Based on the evaluation metrics, the immediate rewards of the POMDP model can be assigned, and consequently a suboptimal policy for choosing the length of each sleep window can be constructed afterwards.

5.3 Sleep Window Determination Policy

According to the evaluation metrics described in the previous section, an energy cost-based sleep window selection policy is picked for the proposed PSWD approach, where the *reciprocal* of the average energy cost is utilized for immediate rewards $r(s_{d\_i}, s_{u\_k}, a_n) \in \mathcal{R}$ of the POMDP model. The reward is designated via a succinct Reward Assignment Algorithm as illustrated in Algorithm 1. It is noticed that the algorithm also takes the tolerable packet delay δ into account in order to draw the adequate length of sleep windows. As shown in Algorithm 1, if the expected delay of state/action pair (s_{d_i}, s_{u_k}, a_n) calculated by (5.8) satisfies the delay constraint δ, the immediate reward $r(s_{d\_i}, s_{u\_k}, a_n)$ is assigned in accordance with the value from (5.5). Otherwise, a pre-defined value $1/\overline{E}_{max}$ is given so that infeasible action would be ruled out from $\mathcal{A}$ corresponding to the traffic states $(s_{d\_i}, s_{u\_k}) \in \mathcal{S}$.

Given the sets $\mathcal{S}$ and $\mathcal{A}$, Algorithm 1 is considered a *table-lookup* algorithm since $\overline{E}(s_{d\_i}, s_{u\_k}, a_n)$ and $\overline{E}_{max}$ can be calculated in advance. Therefore, the time complexity of the algorithm becomes $O(|\mathcal{S}||\mathcal{A}|)$, where $|\mathcal{S}|$ and $|\mathcal{A}|$ represent the number of states and the number of actions in $\mathcal{S}$ and $\mathcal{A}$ respectively.

Algorithm 1: *Reward Assignment Algorithm*

Input: $\mathcal{S}$, $\mathcal{A}$, tolerable delay δ
Output: set of immediate rewards $\mathcal{R}(\mathcal{S}, \mathcal{A})$
foreach $s_{d\_i} \in \mathcal{S}_d$ **do**
    foreach $s_{u\_k} \in \mathcal{S}_u$ **do**
        foreach $a_n \in \mathcal{A}$ **do**
            if $\overline{D}(s_{d\_i}, s_{u\_k}, a_n) \le \delta$ **then**
                $r(s_{d\_i}, s_{u\_k}, a_n) \leftarrow \frac{1}{\overline{E}(s_{d\_i}, s_{u\_k}, a_n)}$
            else
                $r(s_{d\_i}, s_{u\_k}, a_n) \leftarrow \frac{1}{\overline{E}_{max}}$
            end
        end
    end
end

The optimal solution of sleep window selection problem is unavailable owing to the reason of unobservable traffic states. However, thanks to the belief states of POMDP model, the unobservable traffic states can thus be estimated. Furthermore, the reward of an action made in a given traffic state can be acquired by the immediate reward set $\mathcal{R}$. Based on these two kinds of information, the suboptimal choice can be made via adopting a T-step value function in the PSWD approach. The final decision of sleep window selection at the decision epoch $d_t \in \mathcal{D}$ can be determined as

$$D^{(d_t)}\left[(b(s_{d\_i}^{(d_t)}), b(s_{u\_j}^{(d_t)}))\right] = \arg V^{(d_t)}\left[b(s_{d\_i}^{(d_t)}), b(s_{u\_j}^{(d_t)})\right] = \arg \max_{a_n^{(d_t)} \in \mathcal{A}} \left\{ \Gamma^{(d_t)}\left[b(s_{d\_i}^{(d_t)}), b(s_{u\_j}^{(d_t)})\right] \right\}, \tag{5.9}$$

where

$$\Gamma^{(d_t)}\left[b(s_{d\_i}^{(d_t)}), b(s_{u\_j}^{(d_t)})\right] = \sum_{s_{d\_i}^{(d_t)} \in \mathcal{S}_d} \sum_{s_{u\_j}^{(d_t)} \in \mathcal{S}_u} b(s_{d\_i}^{(d_t)}) b(s_{u\_j}^{(d_t)}) r(s_{d\_i}^{(d_t)}, s_{u\_k}^{(d_t)}, a_n^{(d_t)})$$
$$+ \gamma^{(d_t+1)} \sum_{z_{d\_x}^{(d_t+1)} \in \mathcal{Z}_d} \sum_{z_{u\_y}^{(d_t+1)} \in \mathcal{Z}_u} Pr(z_{d\_x}^{(d_t+1)} | a_n^{(d_t)}, \mathcal{B}_d(d_t)) Pr(z_{u\_y}^{(d_t+1)} | a_n^{(d_t)}, \mathcal{B}_u(d_t))\, V^{(d_t+1)}\left[b(s_{d\_i}^{(d_t+1)}), b(s_{u\_j}^{(d_t+1)})\right], \tag{5.10}$$

with $r(s_{d\_i}^{(d_t)}, s_{u\_k}^{(d_t)}, a_n^{(d_t)})$ selected as either $1/\overline{E}(s_{d\_i}^{(d_t)}, s_{u\_k}^{(d_t)}, a_n^{(d_t)})$ or $1/\overline{E}_{max}$ according to Algorithm 1. The function $V^{(d_t)}\left[b(s_{d\_i}^{(d_t)}), b(s_{u\_j}^{(d_t)})\right]$ in (5.9) is defined as the T-step value function for the energy-cost based sleep window determination policy at a decision epoch d_t which starts at d_t, and there are $T-1$ decision steps remaining. The first item of (5.10) denotes the *immediate reward* for the belief state pair $b(s_{d\_i}^{(d_t)}) \in \mathcal{B}_d(d_t)$ and $b(s_{u\_j}^{(d_t)}) \in \mathcal{B}_u(d_t)$. The *expected reward* of the future belief state $\left[b(s_{d\_i}^{(d_t+1)}), b(s_{u\_k}^{(d_t+1)})\right]$ is represented in the second term. Besides, the items of conditional probabilities can be acquired from the denominator of (5.3). The parameter $\gamma^{(d_{t+1})}$ stands for a discount factor of the d_{t+1}-step for convergence control of the future value function. In other words, the value function $V^{(d_t)}\left[b(s_{d\_i}^{(d_t)}), b(s_{u\_j}^{(d_t)})\right]$ intends to determine an action with the maximum reward (i.e. the minimum energy consumption) according to the currently estimated traffic state and the expected rewards result from future actions made in the subsequent states.

Chapter 6

Performance Evaluation

6.1 Model Validation

This section provides the validation of the proposed analytical models by comparing with simulations. Both the sleep ratio and the mean packet delay are evaluated versus arrival rate λ, where λ is selected as $\lambda = \lambda_d + \lambda_u$ with $\lambda_d = \lambda_u = \lambda/2$, and especially $\lambda^{d,i} = \lambda^{u,i} = 0.01$ packets/frame for 16e. Other parameters utilized in both the analytical models and the simulations are listed as follows: the service time $1/\mu = 1$ frame, the variance of the service time $\sigma^2 = 0$, the length of the (default) listening window $T_L = 1$ frame, and idle period $\tau = 4$ frame. It is noted that the results of analysis are represented by lines and the results of simulation are indicated by symbols.

Fig. 6.1 shows the numerical evaluation of Type I for both 16e and 16m sleep mode operation with different lengths of the initial sleep window/cycle, in which the maximum sleep window/cycle is set to be 16 frame durations. On the other hand, the outcomes of Type II for 16e and 16m are examined in Fig. 6.2. It can be observed from both figures that the results obtained from the analytical models are consistent with the that acquired from the simulation results, which validate the correctness of

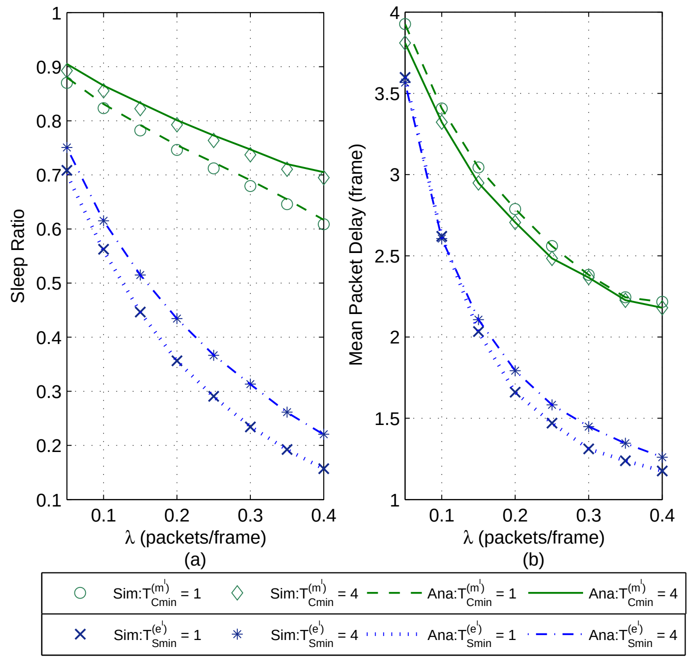

Figure 6.1: Numerical evaluation for Type I of the IEEE 802.16e/m with: (a) sleep ratio vs. packet arrival rate λ; (b) mean packet delay vs. packet arrival rate λ.

the derived models. There are small amounts of deviation in the results of the sleep ratio as observed from Fig. 6.1(a) and the mean packet delay in Fig. 6.2(b), which are primarily caused by the approximation with the derivation of $\omega^B_{\eta,n}$ in (3.17) and $E[W_{L_i}]$ in (4.32), respectively. In both Fig. 6.1(a) and Fig. 6.2(a), the sleep ratio decreases when the traffic load λ is augmented, and it is obvious to observe that 16m performs better while that of 16e degrades dramatically. As for the mean packet delay of both Type I and Type II of 16e and 16m , as shown in Fig. 6.1(b) and Fig. 6.2(b), the operation of 16m owns somewhat higher values than the 16e, however, such packet delays still meet the requirements for individual traffic types, that is, BE traffic for Type I; while the bounded characteristics for QoS-guaranteed services for Type II. These phenomenons are mainly attributed to the differences between 16m and 16e mentioned in Section 2.3. Without the existence of idle periods, the AMS in 16m can

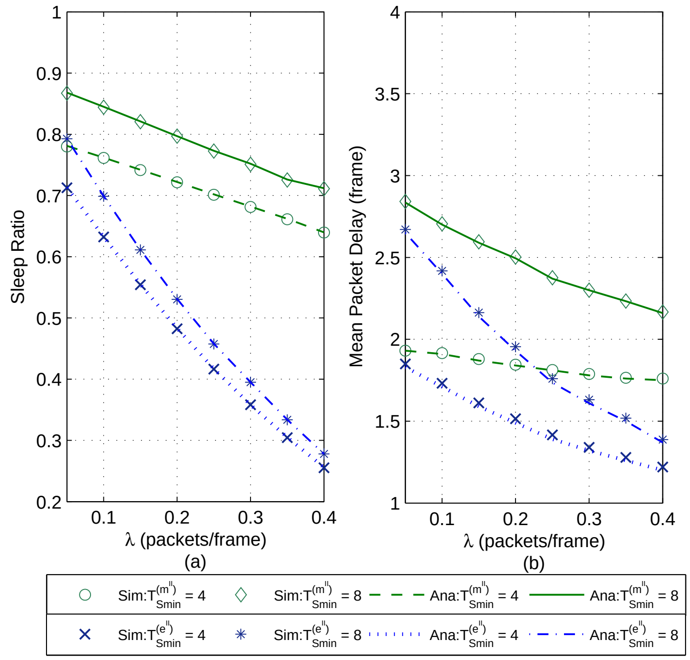

Figure 6.2: Numerical evaluation for Type II of the IEEE 802.16e/m with: (a) sleep ratio vs. packet arrival rate λ; (b) mean packet delay vs. packet arrival rate λ.

return to sleep window as soon as it completes data transmission, and energy can be conserved. Nevertheless, the opportunities to immediately receive the incoming packets are diminished and consequently incurs slightly more packet delays. On the other hand, the MS of 16e almost stays in the normal (active) mode when lying in heavy traffic, which leads to poor power-saving performance.

6.2 Performance Comparison

In this section, simulations are conducted in order to evaluate the performance of the proposed PSWD approach. It is also in comparison with the behavior of sleep mode operations for IEEE 802.16e and 802.16m in aspect of either Type I or Type II. A single BS/MS (ABS/AMS) pair is considered as the simulation scenario. All the required negotiations and parameter update procedures among both ABS and AMS for the sleep mode operation implemented via an MATLAB event-driven simulator. It is noted that the traffic state estimation process, calculation of evaluation metrics, and the sleep window determination policy of the proposed PSWD approach are all executed only at the ABS side and then inform the affiliated AMS about the next action to be undertaken, since the ABS has no power-saving concern. Consequently, the AMS should also provide its own UL traffic information observed during the previous sleep window to the serving ABS via control messages originally defined in the IEEE 802.16m standards. The parameters adopted in the simulations are list in Table I wherein the values of energy consumption are in light of the industrial manufactured mobile WiMAX chip [30].

TABLE I : SIMULATION PARAMETERS

Parameter	Value
Frame duration	5ms
Idle period (τ)	4 frames
Initial sleep window/cycle length of Type I for 16e/16m	1 frame
Maximum sleep window/cycle length of Type I for 16e/16m	128 frames
Overall sleep window length of Type II for 16e&16m	4 frame
Default listening window length	1 frame
Energy consumption per busy frame (ε_B)	280 mW
Energy consumption per idle frame	120 mW
Energy consumption per sleep frame (ε_S)	10 mW
Energy consumption per state switching (ε_{SW})	1 mW
Mean service rate (μ)	3 packets/frame

Each simulation run is carried out for 10 minutes, and every acquired outcome with the individual mean arrival rate is averaged from 100 simulation runs. Furthermore, it is noted that a 3-step value function is utilized in the PSWD approach, where the

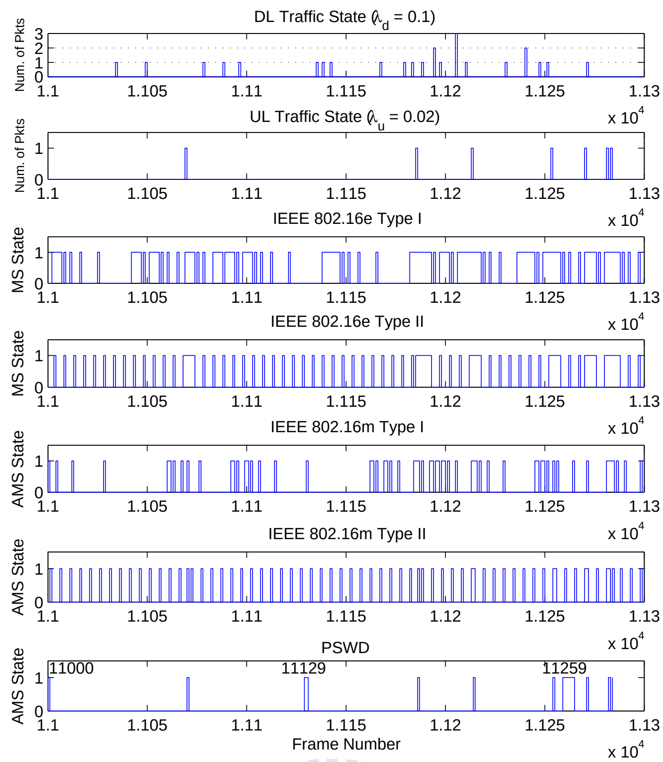

Figure 6.3: An exemplified sleep mode operation among Type I/II of IEEE 802.16e/m and PSWD approach.

discount factor γ for the future ith step value function is chosen as $(0.5)^i, i = 1, 2$, for the reason that the rewards in later time are considered less influential to the present action.

Fig. 6.3 depicts a exemplified timing diagram of sleep mode operation among all above schemes, including the IEEE 802.16e, the IEEE 802.16m, and the proposed PSWD approach under packet arrival rates of $\lambda_d = 0.1$ and $\lambda_u = 0.02$. The two subplots from the top show the number of arriving packets from DL and UL directions, respectively, within the frame duration $[11000, 11300]$ of the simulation. The corresponding operations of each scenario are presented in the remaining subplots below, where it is noticed that the state "1" represents that an MS/AMS is staying in the normal mode or in listening windows; while the status of power-saving, i.e. sleep state

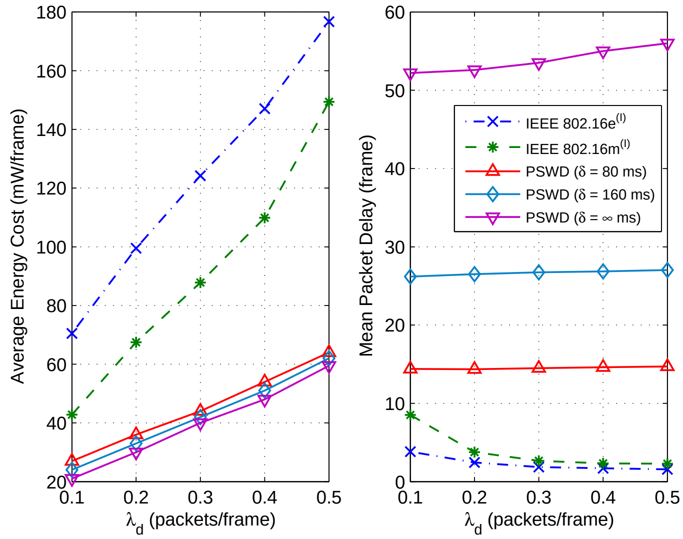

Figure 6.4: Performance comparison among Type I of IEEE 802.16e/m and PSWD approach under NRT/BE traffic.

of an MS/AMS is denoted as state of "0". As can be observed from Fig. 6.3, the characteristics of individual scheme is obviously performed, e.g. Type I of 16e/m is suitable for non real-time and BE traffic, on the other hand, Type II is preferred for real-time traffic-only or real-time and BE-traffic mixed scenarios thanks to its periodic traits. The 16e MS of either Type I or Type II tends to spend more time duration in the awake state than the 16m AMS due to the defect of existence of the normal mode in 16e. Nevertheless, compared to the proposed PSWD approach, both 16e and 16m seem to be inefficient on account of numerous under-utilized listening windows caused by adopting the binary-exponential growing mechanism. The AMS of PSWD almost keeps staying in the sleep state (the awake states of listening widows are at frame number 11000, 11129 − 11130, and 11259 − 11264, and remainders are resulted from the interruptions due to UL transmission), since each sleep window is determined by rewards of the POMDP model according to the estimated present traffic state.

Fig. 6.4 shows performance comparisons between 16e, 16m, and the proposed PSWD approach over various arrival rates of DL traffic with loose delay constraints, such as BE and non-real-time traffic. Each λ_d is an average value from the dMMPP traffic model, and the arrival rate of UL traffic is fixed at $\lambda_u = 0.02$ packets /frame. Note that as for these traffic types, the performance of mean packet delay is not of great importance, so that it can be turned to achieve higher power-saving efficiency. Due to the Reward Assignment Algorithm in PSWD, the outcomes of mean packet delay satisfy the respective tolerable delay δ [1], as for the case that does not consider any delay constraints, the results are bounded by half the maximum size of sleep window, i.e. the remaining vacation time which equals to $128/2 = 64$ frames. As can be seen from the metric of energy cost, it is expected that the average energy consumption increases with augmented arrival rates of DL traffic. Moreover, the proposed PSWD can acquire the relatively low energy consumption in comparison with the conventional 16e/m scheme, this may be attributed to the selected length sleep window is more accurate than binary-exponential algorithm, which always attempts to fit the traffic from the minimum size of initial sleep window.

On the other hand, the real-time traffic and BE-traffic mixed scenarios with demand of stringent delay constraint are presented in Fig. 6.5, wherein the corresponding power-saving class of Type II are adopted for both 16e and 16m. With similar values of packet delay, the proposed PSWD ($\delta = 20$ ms) can provide better performance with regard to the average energy cost when the arrival rate is augmented ($\lambda_d > 0.5$). It is also observed that each outcome of packet delay for the PSWD approach meets the values of tolerable delay.

Fig. 6.6 tries to investigate the influence of the ratio of DL and UL traffic, for it is of interest that user behavior in the Internet through the IEEE 802.16 WiMAX

[1] Note that the y-axis of the figure about mean packet delay is in unit of frame; while the delay constraint δ comes in ms.

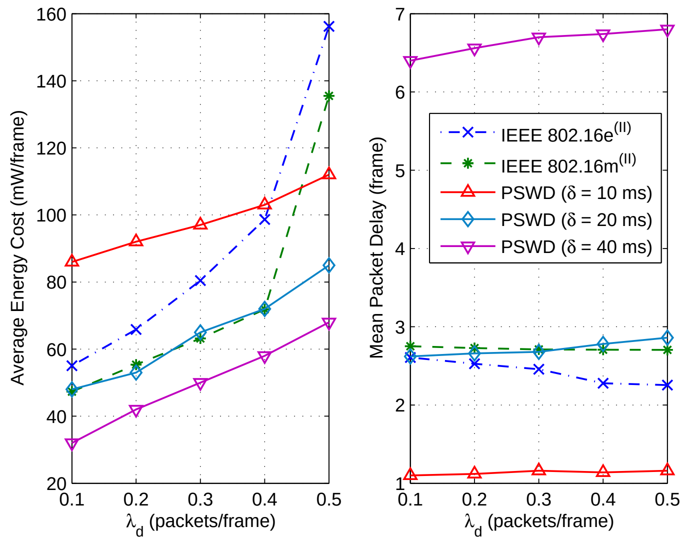

Figure 6.5: Performance comparison among Type I of IEEE 802.16e/m and PSWD approach under RT-only or RT and BE mixed traffic.

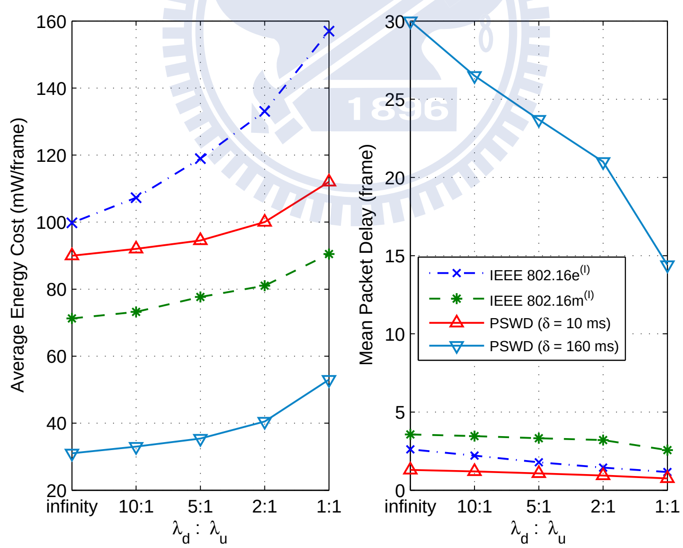

Figure 6.6: Performance comparison among Type I of IEEE 802.16e/m and PSWD approach under different DL/UL ratios.

networks. The x-axis of the figure shows various values of $\lambda_d : \lambda_u$ ratio, where "infinity" corresponds to the situation with only DL traffic. The ratio of "10 : 1" may occur in the case that the user is surfing the Internet by a handhold mobile phone; while a regular user using a computer for watching a video stream via P2P technique may introduce the same amount of traffic between DL and UL (1 : 1). As shown in Fig. 6.6, the more energy cost is required when the proportion of UL traffic becomes higher, since the MS/AMS needs additional duration of time for transmitting the UL packets. The situation is particularly evident as for the case of 16e, wherein the sleep mode of the MS would be interrupted for the occurrence of UL traffic and switched back to the normal mode immediately. On the other hand, the mean packet delay tends to decrease when the DL/UL ratio is augmented due to the reason that during the UL transmission, both DL and UL data transportation are allowed at the same time via the super frame with individual DL-MAP and UL-MAP. It is found that the PSWD with the large delay constraint (δ = 160 ms) gains noticeable improvement since the remaining vacation time has been diminished by half, which turns to be a great quantity in packet delay related to other schemes.

Chapter 7

Conclusions

In this thesis, two comprehensive analytical system models are proposed according to the sleep mode operations of Type I/Type II for the IEEE 802.16e and the IEEE 802.16m broadband wireless networks respectively. Both the downlink and uplink traffic are considered simultaneously, with sleep ratio and mean packet delay as the measures for performance analysis. The effectiveness of the analytical models are validated through numerical simulations. Furthermore, a POMDP-based sleep window determination (PSWD) approach for improving the performance of the sleep mode operation of the IEEE 802.16m is presented. The PSWD approach resolves the length of each sleep window based on the rewards calculated by means of a POMDP model, which speculates the present traffic state via the concept of belief states at each decision epoch. The efficiency of the PSWD approach is evaluated by simulations in terms of energy cost and mean packet delay with tolerable delay taken into account. Simulations show that the proposed PSWD approach outperforms the conventional IEEE 802.16e and IEEE 802.16m corresponding to various traffic demands and satisfies respective delay constraints at the same time.

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