國立交通大學

資訊科學與工程研究所

碩 士 論 文

Mobile WiMAX 系統中
節省即時通訊耗電之封包排程演算法

Energy-Efficient Packet Scheduling Algorithms
for Real-Time Communications
in a Mobile WiMAX System

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摘 要

在寬頻無線存取(Broadband Wireless Access, BWA)的系統中，為了減少行動裝置在網路閒置或使用時的耗電，通常提供了可以彈性利用的睡眠模式(Sleep Mode)。舉例來說，Mobile WiMAX，也就是 IEEE 802.16e，便是其中之一。為了減少行動用戶端(Mobile Subscriber Station, MSS)的耗電，IEEE 802.16e 在睡眠模式的運作上提供了數種省電類別(Power-Saving Class)，各自適合不同服務類型的網路連結(Connection)，以使網路連結的耗電能最小化。不過不幸地，在一個行動用戶端同時啟用多個即時(Real-Time)服務時，先前的研究並不能完全發揮睡眠模式的特性來讓該行動用戶端整體的耗電最佳化。因此在此篇文章中，提出了兩個在 Mobile WiMAX 系統中針對減少即時通訊耗電所設計的封包排程演算法。這兩個方法不但保證了即時通訊所要求的服務品質(Quality of Service, QoS)，同時也盡可能地減少了行動用戶端的耗電，而在模擬的結果中顯示所提出的兩個方法都明顯地勝過傳統的方法。

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ABSTRACT

Broadband wireless access systems usually provide flexible sleep-mode operations for mobile stations to conserve their energy during idle or active mode. For example, Mobile WiMAX, i.e. the IEEE 802.16e, offers several power-saving classes that can be associated with different types of network connections to minimize power consumption of mobile subscriber stations (MSSs). Unfortunately, previous studies did not fully utilize the sleep-mode features to save the energy of an MSS with multiple real-time connections, and power consumption of an MSS is not yet optimized. In this work, two energy-efficient packet scheduling algorithms for real-time communications in a Mobile WiMAX system are proposed. The schemes not only guarantee the quality of services (QoSs) of real-time connections but also minimize power consumption of MSSs. Simulation results demonstrate that the proposed schemes outperform the traditional approach.

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Chapter 1 Introduction

One of the essential features for a broadband wireless access (BWA) system which is designed for portable and battery-operated devices is the power-saving function. For example, the IEEE 802.11, i.e. WLAN, defines a power-saving mode which can be utilized to improve energy efficiencies for web accesses, voice over IP (VoIP), and other applications over WLAN [7][8]. The IEEE 802.16e, so called Mobile WiMAX, that has been newly developed also provides flexible power-saving classes to facilitate mobile subscriber stations (MSSs) to conserve their energy during active and sleep mode [1][2][4]. According to the specification, an IEEE 802.16e MSS can switch to sleep mode for a sleep period, and wakes up to send or receive packets in a listen period. During sleep periods, a base station (BS) must buffer incoming packets sent to the MSS, and then after the MSS switches to listen periods, the BS sends the queued packets to the MSS. To accommodate different characteristics of applications and services, the IEEE 802.16e specifies three power-saving classes and each power-saving class implies a particular sleep and listen behavior for an MSS. An MSS can thus associate a power-saving class with a connection and negotiates the parameters of the power-saving class such as the time to sleep and listen, and the length of each sleep and listen period with the BS for the connection. Obviously, the parameters of a power-saving class associated with a network connection should be carefully decided in order to maximize the energy efficiency of an MSS without violating the QoS requirements of that connection. The QoS issue for a Mobile WiMAX system attracted considerable interest from both academia and industry [3][5][9][10], and the power consumption problems of the IEEE 802.16e to support non-real-time connections have been also studied [6]. Unfortunately, to minimize power consumption of an IEEE 802.16e MSS with multiple real-time connections has not yet been investigated. In this study, two energy-efficient packet scheduling schemes that maximize sleep periods of an MSS and also guarantee the QoSs of real-time connections on an MSS are proposed.

The rest of the paper is organized as follows. The IEEE 802.16e sleep-mode operations and the power consumption problems for an MSS with multiple real-time connections are described in Section II. The proposed scheduling schemes, called periodic on-off scheme (PS) and aperiodic on-off scheme (AS), are presented in Section III. The simulation results are discussed in Section IV, and finally, Section V concludes this study.

Chapter 2 Problem Statement

2.1 IEEE 802.16e Sleep-Mode Operations

In a Mobile WiMAX system, an MSS can switch to sleep mode if there is no packet to send or receive in order to save power. The IEEE 802.16e defines three power-saving classes to accommodate network connections with different characteristics. According to the specification, each connection on an MSS can be associated with a power-saving class, and connections with a common demand property can be grouped into one power-saving class. The parameters of a power-saving class, i.e. the time to sleep and listen, the length of a sleep period and a listen period can be negotiated by a BS and an MSS.

The type-one power-saving class specifies that an MSS sleeps for a period, wakes up to listen incoming packets, and repeats sleep and listen operations. If there is no packet to send or receive during a listen period, an MSS doubles the period for the next sleep. This power-saving class is suitable for the connections of web browsing or data access services. The type-two power-saving class requires an MSS to repeat the sleep and listen in a round-robin basis, and the sleep and listen period are fixed. This sleep mode is appropriate for real-time connections such as VoIP and video streaming services that have packets to send or receive periodically. Based on the type-two sleep mode, an MSS only needs to wake up to send or receive packets in those listen periods without violating the QoSs of the real-time connections. The type-three power-saving class defines the length of a sleep period, and an MSS sleeps for that period and then returns to the normal operation. Figure 1 illustrates examples for the three power-saving classes.

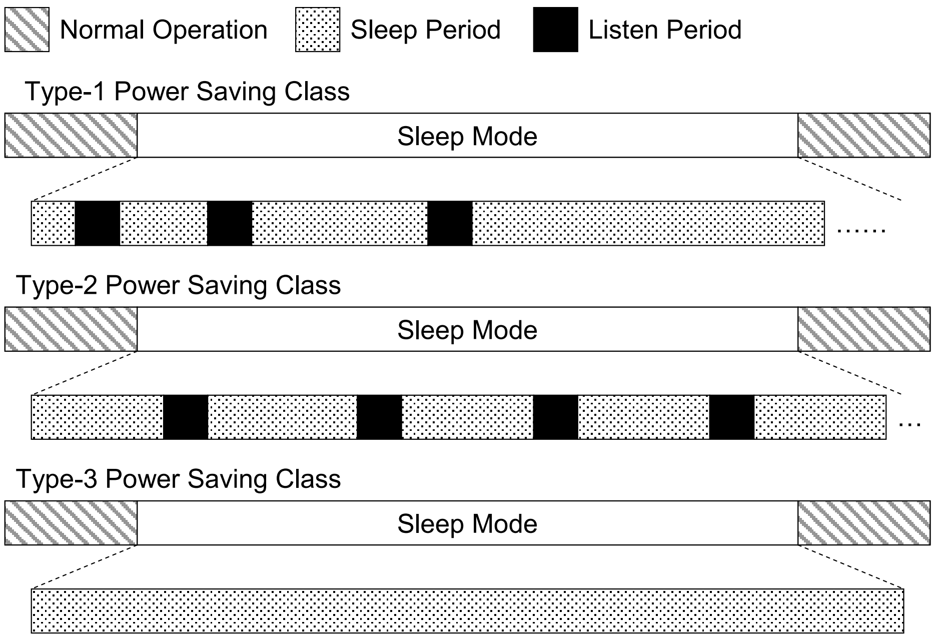

Figure 1. Power-saving classes defined in the IEEE 802.16e

2.2 The Power Consumption Problem

If an MSS establishes multiple connections with different demand properties, the periods that an MSS can sleep are determined by the sleep-mode behaviors associated with all connections. Figure 2 shows an example that an MSS has three connections. The connections have different demand properties, and associate with their preferred power-saving classes and parameters. It can be seen that the actual periods that an MSS can sleep are the slots that three connections are all in a sleep period. Obviously, without a proper schedule of the sleep-mode operations for multiple real-time connections on an MSS, the power consumption of an MSS might not be reduced even the sleep mode is applied.

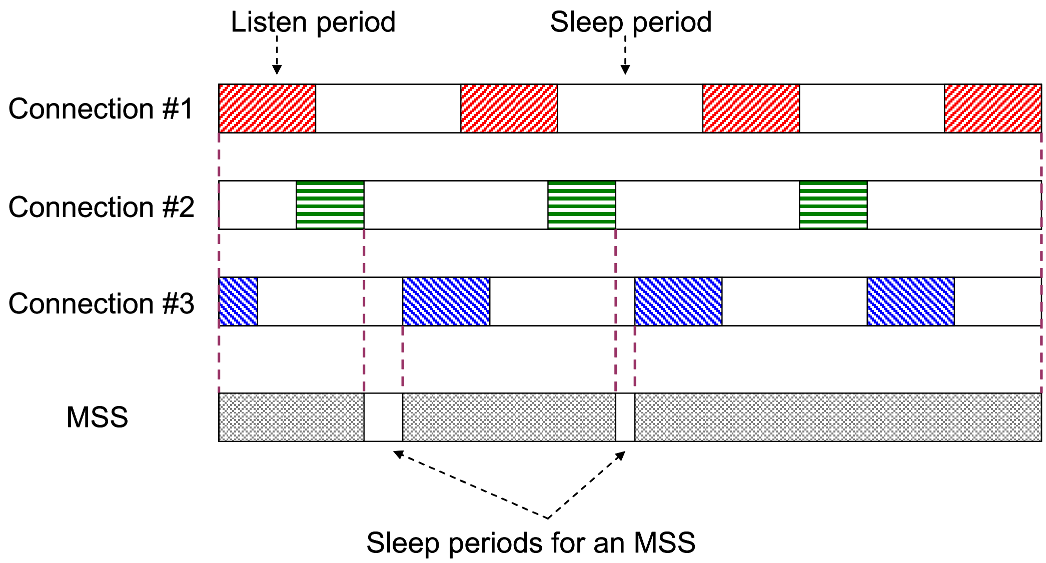

Figure 2. Sleep periods for an MSS with three connections

In this work, only packet scheduling issues for MSSs with multiple real-time connections are considered. Non-real-time packets that can tolerate delays could be scheduled in any listen period with available radio resources for an MSS.

Chapter 3 Proposed Algorithms

3.1 Periodic On-Off Scheme (PS)

The idea behind the first proposed approach, called periodic on-off scheme (PS), is to allow an MSS to sleep for a fixed period and then to listen for another fixed period in a round-robin basis. The scheme maximizes the length of a sleep period in the type-two power-saving class defined in the IEEE 802.16e without violating QoSs of all connections. During listen periods, an MSS transmits and receives packets, and on other hand, the MSS sets the interface idle to conserve the energy during sleep periods. Figure 3 gives an example of a packet schedule for two real-time connections by applying the PS approach.

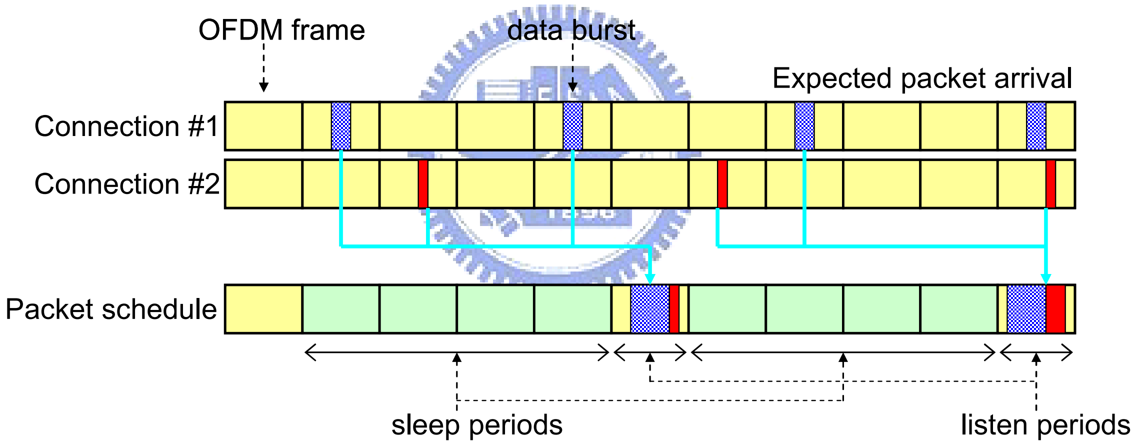

Figure 3. Periodic on-off scheme (PS)

To minimize power consumption of an MSS with multiple real-time connections, the PS determines the length of a sleep period and a listen period under the radio resource and QoS constraints. Considering an MSS with N real-time connections, the QoS parameters of connection i can be denoted as $Q_i\{PS_i, TI_i, D_i\}$, where D_i is the delay constraint of any two consecutive packets for connection i, PS_i is the average packet size for connection i, and TI_i is the average inter-packet arrival time for connection i. Without loss of generality, this study considers the above-mentioned QoS parameters to present the basic idea behind the proposed scheduling schemes. Other parameters such as delay jitters can be also specified as the QoS of a connection and taken into account in the presented approaches.

To satisfy the QoS requirements of the connections on an MSS, both bandwidth and delay constraints specified by all connections need to be considered. For the bandwidth constraint, since an MSS cannot transmit and receive packets during a sleep period, the total amount of packets that an MSS can transmit and receive during a listen period must be large enough to provide the needs for all connections during the listen and sleep period. For the delay constraint, the length of a sleep period must not exceed delay requirements of all connections. Assume the length of an OFDM frame is T_{frame}, and a BS can supply the maximal resources, say B_{frame}, in an OFDM frame to the MSS. The relationship between the number of OFDM frames in a sleep period, say N_S, and the number of OFDM frames in a listen period, say N_A, for the MSS can be derived. First, N_S and N_A must satisfy the bandwidth constraint. That is:

$N_S \geq 0, N_A \geq 0, N_S + N_A \geq 1$,

$$\sum_{i=1}^{N}\left(PS_i \times \left\lceil \frac{(N_S + N_A) \times T_{frame}}{TI_i} \right\rceil\right) \leq N_A \times B_{frame} \tag{1}$$

Equation (1) presents the maximal amount of data that an MSS can transmit and receive during a listen period, i.e. N_A x B_{frame}, must be larger than the total amount of data needed during $N_S + N_A$ OFDM frames for all N connections. Second, N_S and N_A must also satisfy the delay constraint. That is: $(N_S + N_A) \times T_{frame} \leq D_i, i = 1 \sim N$, which means the maximal delay between any two consecutive packets for any connection must be smaller than its delay requirement. Assume that the power consumption of an MSS in sleep mode is P_S, the power consumption of an MSS during listen mode is P_A, and the average power consumption of the

MSS is: $P_{avg} = \dfrac{P_S \times N_S + P_A \times N_A}{N_S + N_A}$. The equation can be rewritten as: $P_{avg} = \dfrac{P_S \times (N_S + N_A) + (P_A - P_S) \times N_A}{N_S + N_A} = P_S + \dfrac{(P_A - P_S)}{\frac{N_S}{N_A} + 1}$. Since P_S is less than P_A, it can be seen from the above equation that the maximal $\dfrac{N_S}{N_A}$ achieves the minimal power consumption of an MSS. By applying the integer programming technique to the above equations, the optimal N_S and N_A under the constraints can be derived. Figure 4 shows an example. After N_S and N_A are determined, an MSS can perform the sleep-mode operations based on the parameters.

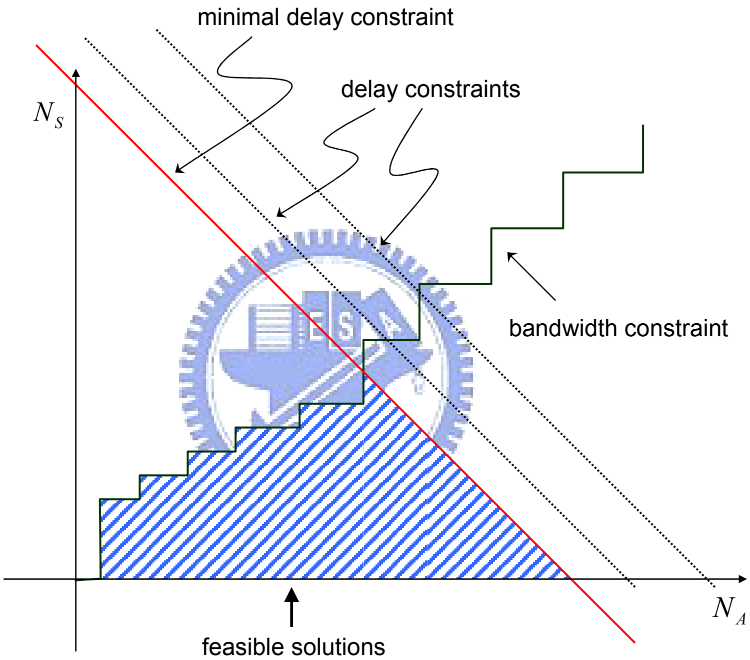

Figure 4. Feasible solutions for the PS scheduling algorithm under constraints

3.2 Aperiodic On-Off Scheme (AS)

Since the PS requires an MSS to always sleep for a fixed period and listen for another fixed period in a round-robin basis, an MSS might have to stay awake in some frames in the listen period even there is no packet to send or to receive. Thus, an aperiodic on-off scheduling scheme (AS) is further proposed to determine if an MSS should go to sleep or not in a frame basis. In other words, the AS tries to schedule the packet transmission in the minimal number of OFDM frames without violating the QoSs of all connections. The length of sleep and listen periods are variable.

While a new connection on an MSS is initiated or any existing connection is released, the AS on a BS is activated to schedule or re-schedule resources in the following frames for the MSS. First, the AS sorts all connections on an MSS based on their delay requirements, and schedules these connections with tight delay requirements first. The reason to schedule connections with tight delay requirements first is that packets of these connections need to be sent or received within a small time window. The scheduler has to consider these packets first in order not to violate their QoSs. Conversely, for packets that could tolerate more delays, the scheduler can find more feasible OFDM frames to schedule the packets without violating the delay requirements. After the scheduler decides the scheduling priorities of connections, the packets from the first priority connection, e.g. connection i, are scheduled. $B_{j,i}$ is defined as the amount of data that are requested by connection i in the j^{th} OFDM frame. The AS tries to group this request with requests from other connections of the same MSS together. Assume that the k^{th} OFDM frame, where $k \geq j$, has been already scheduled B_k bytes data for other requests of the MSS. The AS schedules $B_{j,i}$ into the k^{th} frame if both the bandwidth and delay constraints can be satisfied. That is, $B_{j,i} \leq B_{frame} - B_k$, and $(k - j + 1) \times T_{frame} \leq D_i$. The k^{th} frame can be any frame after the j^{th} frame, but both the bandwidth and delay requirements must be satisfied. In the next paragraph, the determination of the frame k is discussed.

The AS has to schedule $B_{j,i}$ between the j^{th} frame and the $j + \left\lfloor \frac{D_i}{T_{frame}} \right\rfloor - 1^{th}$ frame to satisfy the delay constraint of connect i. Block_Set$_m(B_{j,i})$ is defined as a set of feasible scheduling frames for $B_{j,i}$, i.e. the frames between the j^{th} frame and the $j + \left\lfloor \frac{D_i}{T_{frame}} \right\rfloor - 1^{th}$ frame which have available resources for MSS m. To allocate radio resources in one or more frames from Block_Set$_m(B_{j,i})$ to $B_{j,i}$, the AS follows the below steps. (1). The frames in Block_Set$_m(B_{j,i})$ that have been already scheduled packets for the MSS, called in-used frames for MSS m, receive the highest priorities to be scheduled to $B_{j,i}$. That is because the AS aims to reduce the number of listen frames and increase the number of sleep frames. For a frame which is already scheduled packets, an MSS cannot sleep. Therefore, in-used frames are assigned first if the resources of the in-used frames are still available to accommodate $B_{j,i}$. (2). If there are two or more in-used frames in the set, the AS schedules the packet to the first feasible in-used frame. That is, the AS picks up the q^{th} frame rather than the p^{th} frame if the frame q and p are both in used and $q \leq p$. The reason that the AS should schedule the packet as early as possible is to reduce the delays. Moreover, the p^{th} frame has opportunities to be scheduled for sending or receiving packets whose deadlines are after the q^{th} frame, but the q^{th} frame cannot be scheduled for serving these packets. (3). If the AS cannot find in-used frames from the set or the in-used frames are all fully occupied, un-used frames are scheduled. The AS picks up the last un-used frames from the set to serve $B_{j,i}$. The last un-used frame is selected is because once a frame is scheduled to transmit or receive packets, the frame becomes an in-used frame and the MSS is unable to sleep. If a latter frame can be selected, this frame potentially gains more opportunities to serve other packets in the following OFDM frames. Therefore, the last un-used frame is assigned. Figure 5 illustrates an example of a packet schedule by applying the proposed AS. The AS tries to schedule the packets in the minimal number of frames and can also guarantee the QoSs of all connections. Different from the PS which defines the fixed length on and off periods, the AS needs to exchange the on-off schedule information for each frame between an MSS and a BS. The exchange can be done once after the connection is established or can be performed between an MSS and a BS periodically. The proposed AS approach can be implemented by utilizing the type-three power-saving class defined in the IEEE 802.16e.

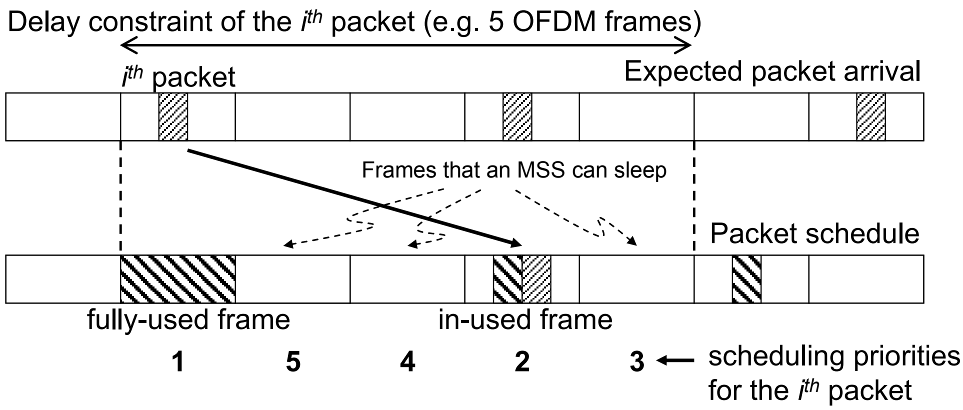

Figure 5. Aperiodic on-off scheme (AS)

3.3 Proposed Schemes for Multiple MSSs

The proposed scheduling schemes presented in the previous paragraphs consider multiple connections on a single MSS, but usually a BS serves multiple MSSs. Therefore, to apply the PS and AS to a BS for scheduling multiple MSSs should be further discussed. The proposed schemes both assume that a BS supplies the amount of resources, say B_{frame}, in an OFDM frame to an MSS. Given the amount of resources allocated to an MSS, the BS determines the parameters of the sleep operations for the MSS. According to Equation (A), the maximal amount of resources in an OFDM frame that a BS can supply an MSS significantly influence the length of a sleep and listen period of the MSS for the PS approach. Also, for the AS approach, the listen and sleep frames are derived from Block_Set$_m$($B_{i,j}$) which is obtained based on the available resources that a BS can offer the MSS. Hence, various resource allocation policies that assign different amount of resources to MSSs result in different power consumption for each MSS. The optimal solution is to properly allocate resources of an OFDM frame to all MSSs so that the total sleep periods of all MSSs are maximal. Unfortunately, the optimal solutions for both PS and AS are difficult to implement since that the available resources of an OFDM frame change while a new connection is established or an existing connection is released. Then, the resource allocations in an OFDM frame to all MSSs and the sleep-mode operations of all MSSs need to be rearranged while the current available resources are updated. The rearrangement of the resources and updates of sleep-mode operations for all MSSs introduce management overheads. Therefore, a greedy strategy that is easy to implement is proposed to cooperate with the PS and AS for a BS to determine the resource allocations for MSSs.

A BS performs the admission control when an MSS requests a new connection. Once a BS receives the connection request, the BS allocates all of its available resources to this new connection request and determines the lengths of the sleep and listen periods for the MSS according to the PS or AS approach. If an MSS releases a connection or establishes a new connection, the BS re-schedules the sleep-mode operations for that MSS based on the current available resources. On the other hand, if an MSS does not establish or release connections, a BS does not re-schedule that MSS even when the BS obtains new resources released by other MSSs. The simulations in the next section demonstrate that the proposed PS and AS approach with the greedy resource allocation policy also efficiently improve the sleep periods for multiple MSSs.

Chapter 4 Simulation Results

4.1 Simulation Environments

An IEEE 802.16e MAC-layer simulator written in C++ was developed to evaluate the performance improvement by employing the proposed schemes. The simulations in this study use WirelessHUMAN(-OFDM) profile, i.e. ProfP3_10 defined in [1], and 10MHz channel, 5ms frame length, and 64-QAM with 3/4 coding rate are assumed. The changes of channel conditions and the adaptive modulation and coding (AMC) are not considered in the simulation. In the simulations, an MSS could be a standard mobile station which establishes multiple real-time connections such as a multi-party conference call, or a mobile relay router which bridges multiple real-time connections for other MSSs. These connections on an MSS have different QoS requirements and real-time characteristics. Four types of real-time connections with different QoS requirements are defined and their descriptions are summarized in Table 1. The voice connections are assumed constant-bit-rate (CBR), and they are classified as unsolicited grant service (UGS) connections. On the other hand, the video connections are variable-bit-rate (VBR). The sizes of video packets are generated by a Gamma distribution suggested by [11]. The video connections are classified as real-time polling service (rtPS) connections. Also, IP/UDP/RTP and MAC headers and the signaling overheads to exchange the control messages of sleep-mode operations for the proposed PS and AS are all taken into considerations in the simulation program.

Table 1. Four real-time connections with different characteristics

Connection	Description
A_L	Low bit-rate voice connection using G.723.1 codec at 6.4Kbps and 30ms frame length
A_H	High bit-rate voice connection using G.711 codec at 64Kbps and 20ms frame length
V_L	Low bit-rate video connection at 100Kbps and 30 frames per second
V_H	High bit-rate video connection at 300Kbps and 30 frames per second

4.2 Simulation Results and Analysis

First, the power consumption of an MSS by employing three different scheduling schemes, i.e. the proposed PS and AS, and the traditional approach, are investigated. The traditional approach implies that each connection associates with its preferred power-saving class and parameters which minimize the packet delay and power consumption for that single connection. In the first simulation, the percentage of sleep periods of an MSS is evaluated while a BS serves different number of MSSs simultaneously. In this simulation, each MSS establishes four real-time connections that could be two high bit-rate voice and two high bit-rate video connections denoted as (A_H+V_H)x2, two low bit-rate voice and two low bit-rate video connections denoted as (A_L+V_L)x2, and one low bit-rate voice and one low bit-rate video connection and one high bit-rate voice and one high bit-rate video connection defined as $A_L+V_L+A_H+V_H$. The delay constraints for voice and video connections are set to 50ms and 100ms, respectively. Arrival time of a voice or video packet to the destination that exceeds its delay constraint is counted as a dropped packet. In the simulation, the three packet scheduling schemes all guarantee the packet drop rate to be less than 1%.

Figure 6 shows the percentage of sleep periods for an MSS under different BS loadings, i.e. under that a BS serves different number of MSSs simultaneously. The higher percentage of sleep periods an MSS stays, the less energy the MSS consumes. The simulation results first indicate for an MS with (A_H+V_H)x2, (A_L+V_L)x2, and $A_L+V_L+A_H+V_H$ connections, the maximal numbers of serving MSSs for a BS are about 30, 42 and 35 without violating the packet drop rate and packet delay constraints, respectively. The PS (denoted as $(A_H+V_H)x2$:PS, $(A_L+V_L)x2$:PS, and $A_L+V_L+A_H+V_H$:PS), AS (denoted as $(A_H+V_H)x2$:AS, $(A_L+V_L)x2$:AS, and $A_L+V_L+A_H+V_H$:AS) and traditional (denoted as $(A_H+V_H)x2$:TR, $(A_L+V_L)x2$:TR, and $A_L+V_L+A_H+V_H$:TR) scheduling schemes achieve similar performance in terms of the maximal numbers of serving MSSs for a BS while the delay and packet drop rate can be guaranteed. Regarding of the percentage of sleep periods of an MSS, the simulation results reveal that the AS achieves the best performance among three approaches. By employing the AS, an MS always can have more than 75% sleep periods, about 50% to 80% improvement than the traditional approach. While the system loading is not heavy, an MSS can have 90% sleep periods, i.e. 80% to 120% improvement than the traditional approach. The reason is that the AS minimizes the number of listen frames and also guarantees the QoS requirements of the connections. On the other hand, the percentage of sleep periods of an MSS can be increased about 80% to 120% by employing the proposed PS while a BS serves few MSSs. While the number of serving MSSs for a BS increases, the improvement of the sleep periods for the PS approach decreases. This is because while a BS suffers from moderated or heavy loading, it is difficult for a BS to find sufficient radio resources in few consecutive frames to accommodate an MSS to perform regular on-off transmissions. Although the improvement of the percentage of sleep periods for an MSS by applying the PS decreases while a BS serves more MSSs, an MSS always gain more sleep time than that by applying the traditional approach.

Figure 7 shows the average packet delay for an MSS under different BS loadings. The figure reveals that the traditional approach always achieves the lowest packet delay since it processes packets immediately while packets arrive. The average packet delays for an MSS by employing the proposed PS are higher than that by employing the traditional approach, but are less than that by employing the AS. This is because the AS may buffer the packet to the maximal delay constraint in order to gain more sleep time for an MSS. Although the delays by employing the proposed PS and AS increase, the QoS requirements of the connections are still satisfied.

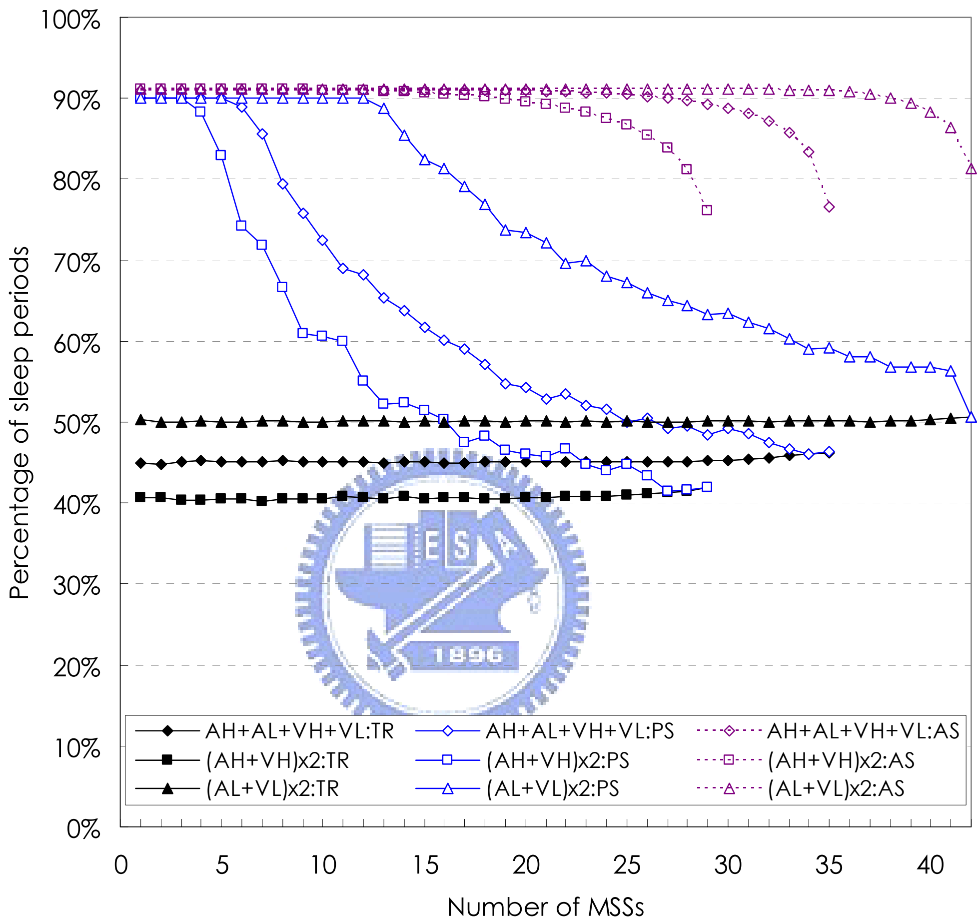

Figure 6. Percentage of sleep periods for an MSS with four real-time connections by employing different scheduling schemes
(**TR**: traditional scheme, **PS**: period on-off scheme, **AS**: aperiod on-off scheme)

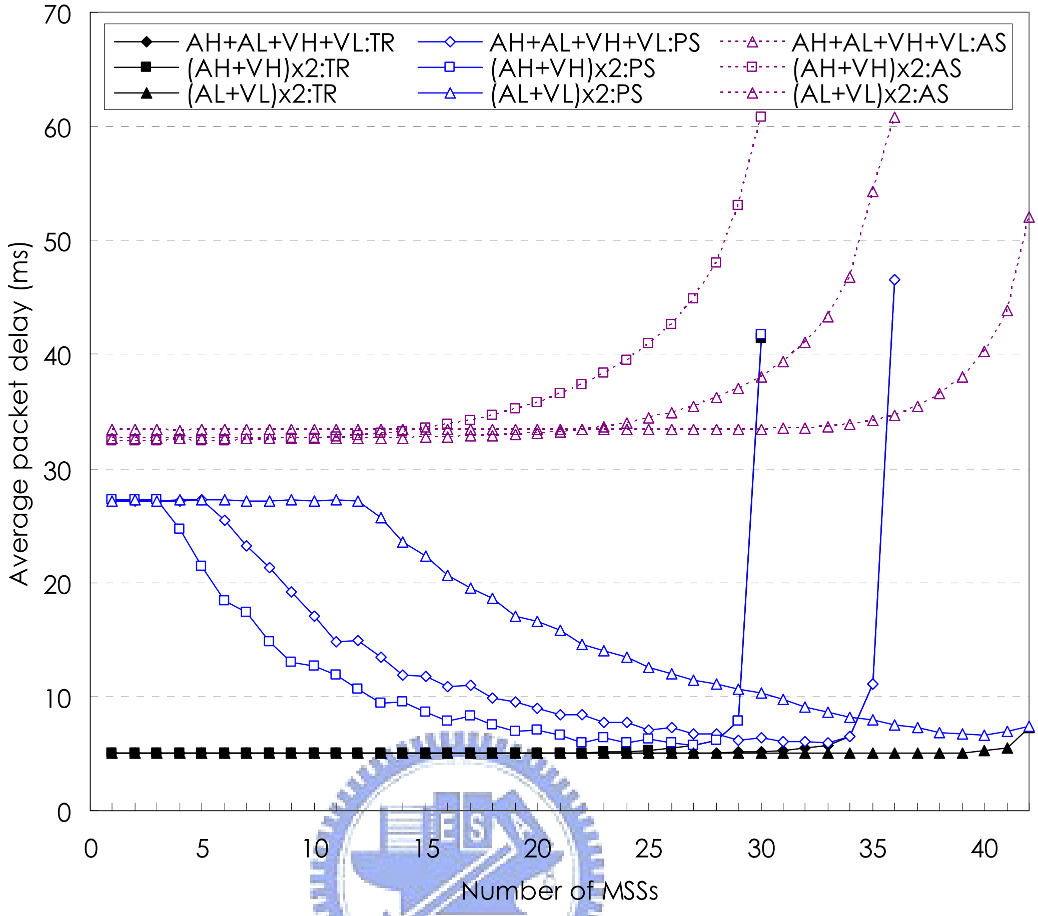

Figure 7. Average packet delay for an MSS with four real-time connections by employing different scheduling schemes

(**TR**: traditional scheme, **PS**: period on-off scheme, **AS**: aperiod on-off scheme)

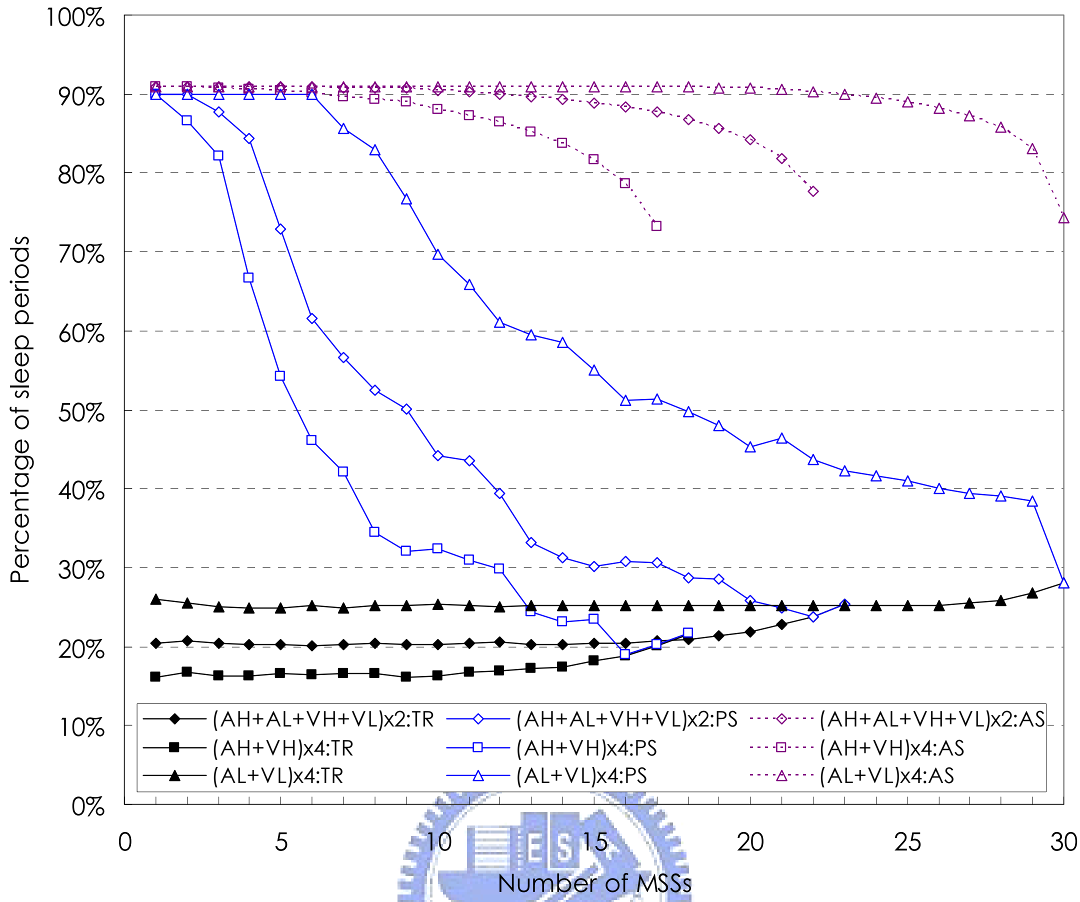

Figure 8. Percentage of sleep periods for an MSS with eight real-time connections by employing different scheduling schemes
(**TR**: traditional scheme, **PS**: period on-off scheme, **AS**: aperiod on-off scheme)

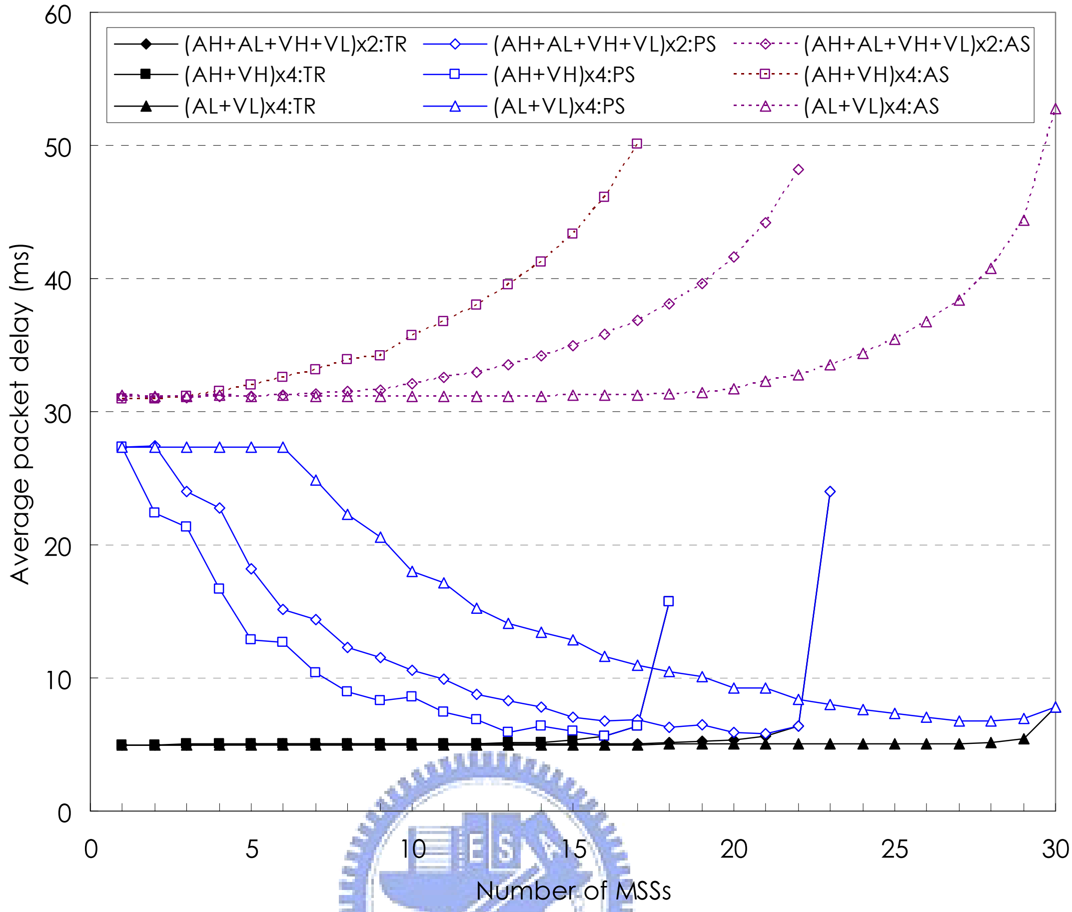

Figure 9. Average packet delay for an MSS with eight real-time connections by employing different scheduling schemes
(**TR**: traditional scheme, **PS**: period on-off scheme, **AS**: aperiod on-off scheme)

In the next simulation, the percentage of sleep periods of an MSS while an MSS has more real-time connections is evaluated. Obviously, if an MSS establishes more real-time connections, the number of MSSs that a BS can serve reduces. Also, in this case, an MSS has more real-time packets to transmit or receive, and an MS must stay awake in more frames to process the packet transmissions. Figure 8 and Figure 9 show the similar results as these in Figure 6 and Figure 7, but each MSS establishes four voice connections and four video connections in this simulation. The real-time connections for an MSS are four high bit-rate voice and four high bit-rate video connections denoted as (A_H+V_H)x4, four low bit-rate voice and four low bit-rate video connections denoted as (A_L+V_L)x4, and two low bit-rate voice connections and two high bit-rate video connections denoted as $(A_L+V_L+A_H+V_H)$x2. As can be seen from the figure, the maximal number of serving MSSs for a BS decreases. Also, the percentage of sleep periods of an MSS decreases to 15% to 20% for the traditional approach. By grouping packets from different real-time connections together and scheduling them in the same frames, the percentage of sleep periods significantly increases. Figure 8 shows that an MSS still can gain 75% to 90% sleep time by applying the proposed AS. While a BS serves 10 MSSs and implements the PS, each MSS can have 50% more sleep time than that by applying the traditional approach. Figure 9 shows that the traditional approach always achieves the lowest packet delay. The average packet delay of an MSS by applying the AS is more than that by applying the other two schemes.

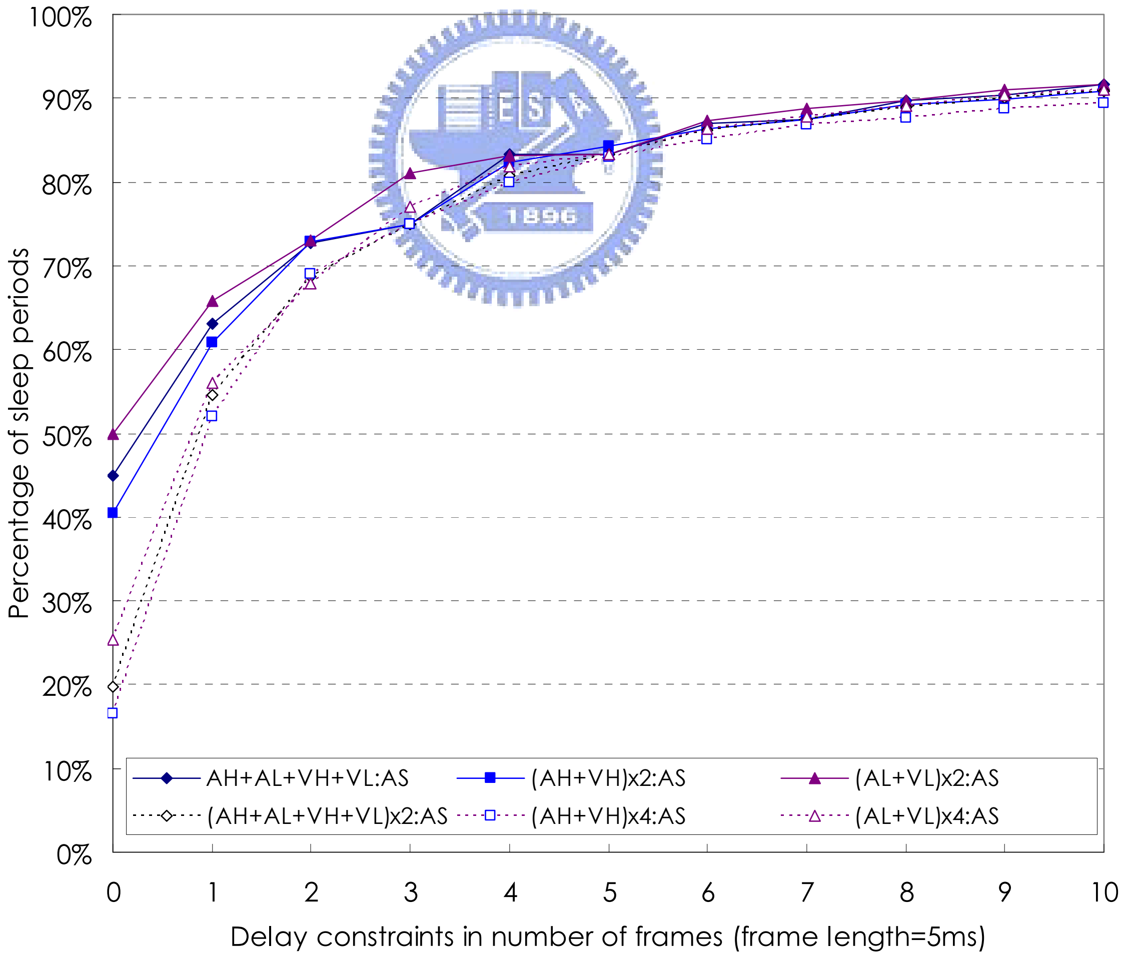

Figure 10. Percentage of sleep periods for an MSS while the AS with different delay constraints is applied

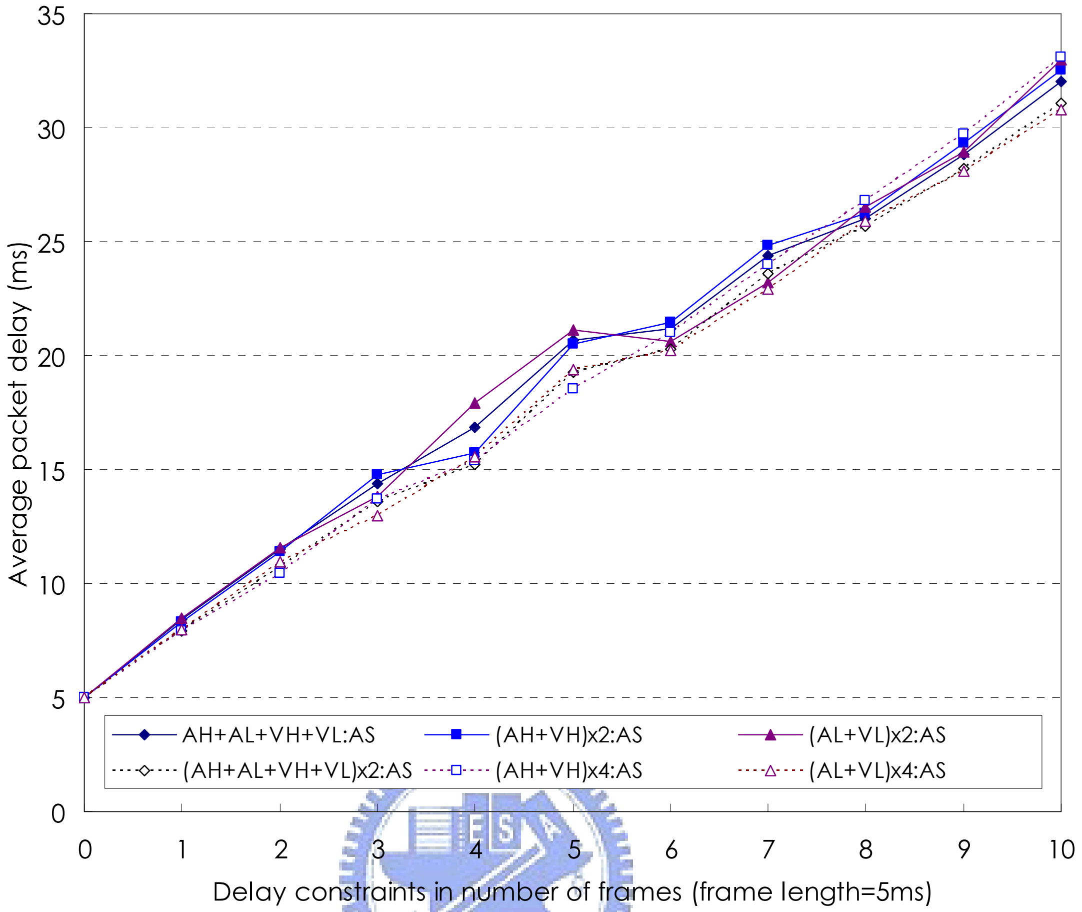

Figure 11. Average packet delay for an MSS while the AS with different delay constraints is applied

Finally, the percentages of sleep periods of an MSS under different delay constraints that real-time connection can tolerate are investigated. Figure 10 shows the percentage of sleep periods of an MSS by applying the AS with different delay constraints. In this simulation, a BS is assumed to have a moderate system loading. The number of serving MSSs is 20 for the situation that each MSS establishes two voice and two video connections, and the number of serving MSSs is set to 10 for the situation that each MSS establishes four voice and four video connections. The delay constrains for both voice and video connections vary from zero OFDM frame, that is 0ms, to 10 OFDM frame, that is 50ms. Notably, if the delay constraint is set to zero frame, the AS must schedule all packets immediately without introducing any delay. Therefore, the AS with 0ms delay constraint for real-time connections becomes the traditional approach. Figure 10 shows that if the zero delay constraint is set, i.e. by applying the traditional approach, the percentage of sleep periods for an MSS with eight and four real-time connections is about 15% to 25% and 40% to 50%, respectively. While the delay constraint for both voice and video connections is set to one OFDM frame, i.e. 5ms, the AS can improve the percentage of sleep periods of an MSS by 15% to 40%. The percentage of sleep periods increases to about 70% to 90% if the delay constraints for real-time connections are set to two OFDM to ten OFDM frames. If the real-time connections can tolerate more delays, loose delay constraints can be set and more percentage of sleep periods for an MSS can be obtained. Although the percentage of sleep periods increases while loose delay constraints are applied, the improvement becomes saturated while the delay constraint is larger than eight OFDM frames. In this situation, the bandwidth constraint becomes the bottleneck and an MSS needs to stay awake to transfer and receive the data in the minimal number of OFDM frames in order not to violating the bandwidth constraints for these real-time connections.

On the other hand, Figure 11 shows the average packet delay of the AS with different delay constraints. As can be expected, the average delay linearly increases by the delay constraints. The average delay for a real-time connection and the improvement of the sleep time are tradeoff for a BS that applies the AS approach. For example, for real-time connections which can tolerate 50ms delay, an MSS with four connections and eight connections by applying the AS gain 50% and 70% more sleep time than that by employing the traditional approach, respectively.

Chapter 5 Conclusions

Two energy-efficient packet scheduling schemes for the IEEE 802.16e were proposed. The proposed periodic on-off scheme that allows an MSS to sleep and listen for fixed periods in a round-robin basis is easy to implement. The aperiodic on-off scheduling scheme (AS) that determines if an MSS should go to sleep or not in a frame basis is further proposed to maximize the length of sleep periods of an MSS. Simulation results demonstrate that the PS approach introduces few packet delays but increases about 80% to 120% sleep periods for an MSS than the traditional approach while a BS serves few MSSs. On the other hand, an MSS employing the proposed AS gains 15% to 120% more sleep periods than that applying the traditional approach depending on the delay constraints and the number of real-time connections on the MSS. The proposed schemes not only minimize the power consumption of MSSs with multiple real-time connections but also guarantee the QoSs of these real-time connections.

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