Enhanced Sleep Mode Operations for Energy Saving in IEEE 802.16e¹

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Abstract. The broadband wireless access (BWA) network, such as IEEE 802.16e, becomes more and more popular in recent years. According to the IEEE 802.16e specifications, mobile subscriber stations (MSSs) with energy constraints are allowed to switch to the sleep mode to reduce their power consumption. Considering a number of service connections on the MSS with different traffic characteristics and requesting different power saving classes, the MSS may not be able to sleep and save energy due to improper schedules of sleep operations for service connections. In this paper, an enhanced longer common sleep time (E-LCST) scheme is proposed and it first schedules realtime packets together in less number of frames without violating their delay constraints. After the listen and sleep frames are determined for transmitting real-time packets, the proposed scheme then considers non-real-time packets and schedules them into the existing listen frames if the resources are available. Therefore, MSSs can have more sleep frames and save the energy. Simulation results have shown that the proposed E-LCST performs 33% to 68% better than the conventional IEEE 802.16e Standard in terms of percentage of sleep periods, which reflects power consumption. Although, the proposed E-LCST introduces a little bit more delay, the QoS requirements of real-time connections are still met

Keywords: Energy consumption, Energy efficiency, IEEE 802.16e, Power saving, Sleep mode, WiMax

1 Introduction

The IEEE 802.16 standard [1] initially considers fixed broadband wireless access (BWA) in which all subscriber stations (SSs) are fixed nodes. The emerging IEEE 802.16e standard [2] enhances the mobility function so that mobile subscriber stations (MSSs) can be supported. The energy saving of mobile devices thus becomes a very important issue, because mobile devices are usually battery-operated. In the IEEE 802.16e, a base station (BS) serves as a control point which schedules radio resources

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for all MSSs attached to the BS. For MSSs, there are two operation modes, i.e. normal mode (or called active mode) and sleep mode. The normal mode is the state that an MSS can transmit and receive data with the BS at anytime. For sleep mode, an MSS has to negotiate the sleep mode parameters with the BS. Then, the MSS can switch between sleep modes which the MSS is unavailable from the BS's perspective and listen modes which the MSS can send and receive packets from the BS. The sleep mode operation intends to minimize the power usage of MSSs [2].

When a connection is established, an MSS can switch to the sleep mode if there is no packet to transmit. The specification defines the sleep mode operation. In the sleep mode operation, the time is divided into fixed sizes, called frames. A frame is the basic unit of time to send, receive and listen. Before entering the sleep mode, the MSS have to send a sleep request frame to the BS. If the MSS gains the approval from the BS, then it will enter the sleep mode. When an MSS enters the sleep mode, it sleeps during the sleep window and wakes up at the listening window to receive the MOB-TRF-IND (mobile traffic indication) message. If there is no buffered packet for itself, it sleeps again until the next listening window. The actions of sleeping and listening with updated size of sleep window are repeated until there is buffered data for the MSS to transmit. The MSS also wakes up from the sleep mode when the MSS has data to transmit to the BS.

The IEEE 802.16e defines three power saving classes for different applications which generate different traffic characteristics. Power saving class is a group of connections that have common demand properties [2]. For different connections between the BS and the MSS, there are different QoS requirements. So we group different connections into different power saving classes to satisfy their QoS requirements. The type I power-saving class specifies that an MSS sleeps for a period, wakes up to listen for incoming packets, and repeats sleep and listen operations. If there is no packet to send or receive during a listen window, an MSS doubles the window for the next sleep. This power-saving class is suitable for the connections of web browsing or data access services such as BE (best-effort) or NRT-VR (non-real time-variable rate) service. The type II power-saving class requires an MSS to repeat the sleep and listen on a round-robin basis, and the sleep and listen windows 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. It is suitable for connections of UGS (unsolicited grant service) or RT-VR service. Based on the type II sleep mode, an MSS only needs to wake up to send or receive packets in those listen windows without violating the QoSs of the real-time connections. The type III power-saving class defines the length of a sleep window, and an MSS sleeps for that window and then returns to the normal operation. Fig. 1, Fig. 2, and Fig. 3 illustrate examples for the three power-saving classes.

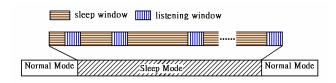


Fig. 1. Operation of power saving classes of type I.

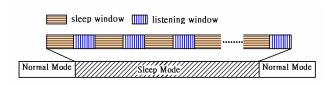


Fig. 2. Operation of power saving classes of type II.

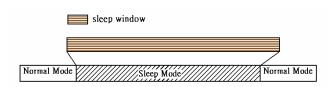


Fig. 3. Operation of power saving classes of type III.

2 Problem Statement and Related Work

There are usually many different connections on an MSS. To switch to sleep mode and save power, an MSS has to consider sleep windows of all service connections. We define the notation "sleep time" as the total periods of sleep windows in the sleep mode for one connection and the notation "common sleep time" as the common periods of sleep time among several connections. Fig. 4 is an example of sleep mode operation with two power saving classes (type I and type II). Each connection has its own sleep time indicated by sleep windows. In the state of the MSS, the periods which are marked as "Sleep Time" is the common sleep time between the two connections. The periods of sleep time is the actual time duration for the MSS to enter the sleep mode to save power. Note that in Fig. 4, each connection has more sleep time in its own sleep mode operation. However, the common sleep time that the MSS can enter the sleep mode is much less than the sleep time of each connection. This is because the listening windows are not at the same time periods between two connections.

To improve the energy efficiency, the MSS needs to prolong the sleep time. The basic idea of the proposed approach is to reduce the number of listening windows by

grouping packets that are originally scheduled to send in multiple listening windows, and send them in one single listening window without violating the delay constraints of different connections so as to lighten the effect of dispersive listening windows.

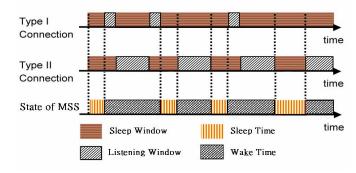


Fig. 4. Example sleep mode operation with two power saving classes.

Several researches focused on the performance analysis of sleep mode operation in the IEEE 802.16e. However most of them only concentrated on the performance analysis of power saving classes of type I. In [3] [4], the authors proposed a model for performance analysis of the sleep-mode operation for energy saving considering both incoming and outgoing frames of MSSs. In [5], it examined the sleep mode operation in IEEE 802.16e in terms of the dropping probability and the mean waiting time of packets in the queue buffer of BS. In [6], they proposed two scheduling algorithms (PS and AS) for power saving classes of type II connections. The schemes minimize the power consumption of an MSS and also guarantee the requirement of QoS. They group packets into the same frame to reduce the number of listening windows. It groups two type II packets into a single frame. The number of listening windows is reduced and the sleep periods increase. As a result, there is more sleep time for the MSS to enter the sleep mode and save more power.

3 Proposed Energy Saving Schemes

There are usually more than one service connections on an MSS. From Fig. 4, we know that if there is more than one connection, the total common sleep time may decrease, because the total common sleep time is the common periods of sleep time among all connections. If we can reduce the number of listening windows in any connection, we can have more total common sleep time among connections, thus have more sleep time to save power. In this paper, we propose two energy saving schemes to increase the length of common sleep time and to enhance the energy saving of sleep mode operation. Our schemes are suited to an environment that has both power saving classes of type I and type II connections. In our schemes, we didn't consider the power saving classes of type III, which is for multicast connections, since we focus on the unicast connections only.

The first scheme is called *Longer Common Sleep Time* (LCST). Because the power saving classes of type II (for UGS, RT-VR) is time-sensitive, we only modify the operation of the power saving classes of type I to have more common sleep time. For type I connections, the MSS wakes up to listen the traffic indication message at each listening window. The MSS returns to sleep mode again when there is no buffered data in the BS. The basic idea of our LCST scheme to removes the listening windows from the power saving classes of type I connections and the traffic indication messages of power saving classes of type I will be handled during the listening windows of power saving classes of type II connections. The reason to do so is because the power saving classes of type I is for connections of BE and NRT-VR, which are time-insensitive.

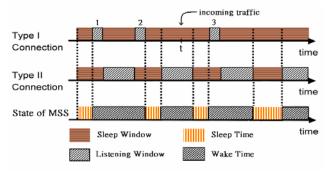


Fig. 5. Original scheme of power saving classes.

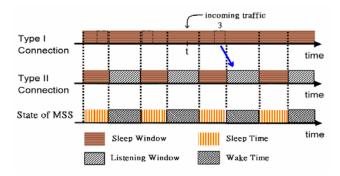


Fig. 6. Proposed method of power saving classes.

In Fig. 5, there are three listening windows in the type I connection. The MSS has to wake three times to listen the traffic indication message. If there is only one data coming at time *t*, in the first and second listening windows, the MSS needs to wake up and then return to sleep right away. We can have longer common sleep time if we can keep sleeping at these two listening windows. In Fig. 6, the proposed LCST method removes the listening windows from the power saving classes of type 1 connection and the traffic indication message transmitted by the BS will be handled during the listening windows of type II connection. For example, in Fig. 6, the incoming traffic at time *t* will be handled during the third listening window of type II connection. The

advantage of our LCST scheme is that for type I connections, the MSS doesn't need to wake up at all to listen the traffic indication messages from the BS. This method reduces the effect of type I connections on common sleep time, and the MSS shall have longer sleep time to enter the sleep mode. On the other hand, the method uses the periodic characteristic of type II connections to read type I traffic indication messages if any. Note that the type II connection wakes up in a fixed period, so the delay of type I connections can be bounded. In summary, this method eliminates of the listening windows of type I connections to save more power while type I connections have bounded delays.

Besides the LCST, we combine the idea of [6] to enhance the LCST scheme. We called it enhanced LCST (E-LCST). This E-LCST scheme groups several type II packets into a single packet in one connection to reduce the number of frames that need to transmit them from BS to MSS. In this way, the sleep periods of this connection can be increased. As a result, the MSS can have more common sleep time among different connections to enter the sleep mode and save more power. The proposed two schemes, LCST and E-LCST are compatible with the original IEEE 802.16e standard in terms of no change of MSSs and no change of the communication mechanism between BS and MSS. The only requirement is that the BS needs to be aware of LCST and E-LCST in order to set appropriate values of T_{min} and T_{max} . For the LCST, assume a type I connection of the MSS sends a request of sleep mode operation to the BS. Then, if the BS permits the request, it will set the parameter T_{init} to a very large number. For this type I connection, the MSS will not wake up periodically to listen to the traffic indication message. If there are buffered packets for the type I connections in the BS, the BS can transmit the packets to the MSS via the frames of type II connections. If the data size of power saving classes of type I is small enough, we can use the unused frame space of a type II connection to transmit. Otherwise, the BS will transmit the data to the MSS in the next frame and the MSS will stay awake to receive the data. For the E-LCST, the BS may group several type II packets that are to be sent in separate frames, into a single frame for transmitting later. In this situation, the BS only needs to adjust T_{min} to allow the MSS to sleep longer. Again, for E-LCST to work, the only requirement is the BS needs to be aware of E-LCST. No other changes are necessary in the MSS or the communications between BS and MSS.

Our schemes are designed for an environment with both power saving classes of type I and type II connections. If there are many connections of type I and less connections of type II, our schemes may not achieve a good performance. Because if too many buffered data have to be transmitted with type II frames, the average packet delay of type I connections will be extended and the advantage of using unused frame space of type II connections will not work well.

4 Simulation Results and Discussion

We wrote a C++ program to simulate and evaluate the performance of LCST, E-LCST and the sleep mode operation in the IEEE 802.16e in terms of the percentage of sleep periods and average packet delay. The percentage of sleep periods, which

reflects the power consumption of an MSS, is defined as (number of sleep frames) / (number of sleep frames + number of listening frames + number of awake frames). The average packet delay is the average elapsed time from the time that a packet enters the BS to the time that the packet completes its transmission to the MSS. The simulation environment is similar to that in [6]. The duration of an OFDM frame is assumed 5 ms, and the maximal data rate that a BS can offer an MSS is assumed 1600 kbps. That is, the frame length is 1000 bytes. Eight different traffic connections were defined and the parameters of them are described in Table 1 and Table 2. Some parameters were referred from [4] and [6] and we modified part of them to demonstrate the energy efficiency of our proposed schemes in every respect.

Connections A, B, C and D are power saving classes of type I, and connections E, F, G and H are power saving classes of type II. The main difference between connections in each type is the variations of packet size and interval of packet arrival. This is to evaluate the performance under different traffic loads. The values of packet size and interval of packet arrival for each packet in type I connections were randomly generated from the ranges specified in Table 1.

Connection	A	В	С	D
Type	I	I	I	I
Packet size (Bytes)	1~1000	1~1000	1000~2000	1000~2000
Sleep Period (ms)	[5, 320]	[5, 160]	[5, 320]	[5, 160]
Interval of packet arrival (ms)	1~350	1~180	1~350	1~180

Table 1. Parameters of type I connections.

Table 2.	Parameters	of type	П	connections

Connection	E	F	G	Н
Туре	II	II	II	II
Packet size (Bytes)	160	160	800	800
Interval of packet arrival (ms)	20	30	20	30
Delay constraint (ms)	100	100	100	100

In Fig. 7, it shows the percentages of sleep periods using the three different schemes (802.16e, LCST and E-LCST). The higher percentage of the sleep period is, the longer common sleep time that an MSS can enter the sleep mode and save more power. The notation A+E means that there are only two connections, A and E. It is a simple traffic environment. By increasing the number of connections, the traffic environment becomes more complex. We found that if the traffic environment becomes more complex, the percentage of sleep periods will become smaller in all the three schemes. In all cases, both the proposed two schemes performed better than the IEEE 802.16e. In Fig. 7, it shows that the percentages of sleep periods of LCST and E-LCST are 14% to 50% and 33% to 68% more than IEEE 802.16e, respectively.

The overhead of the proposed schemes (LCST, E-LCST) is that they have longer average delay than the scheme of IEEE 802.16e. The reason is that we delay the listening windows and reduce the number of listening windows. The buffered data in the BS are sent only after the listening windows of type II connections. However, we bounded the delay. The listening windows were postponed by the evaluation with delay constraint of type II connections. For connections of power saving classes of

type II, we also guarantee their QoS. For the connections of power saving classes of type I, we wouldn't make their average delay longer than the delay constraint of type II

Fig. 8 shows the average packet delay in different traffic environments. For type I (T1) connections, the LCST has 6% to 31% longer average packet delay than the IEEE 802.16e scheme and the E-LCST has 71% to 77% longer average packet delay than the IEEE 802.16e scheme. For type II (T2) connections, the LCST has the same average packet delay as the IEEE 802.16e scheme since the LCST did not modify the sleep mode operation of type II connections. The E-LCST has 84% to 88% longer average packet delay than the IEEE 802.16e scheme. The IEEE 802.16e scheme achieves the lowest packet delay, because its MSS wakes up more frequently to transmit packets. Nevertheless, the simulation results indicate that all schemes, no matter type I or type II connections all satisfied the QoS requirement in terms of delay constraints specified in Table 2.

Since we can bound the average packet delay under the delay constraint of type II connections in our schemes, here we present another simulation results of the percentage of sleep periods and average packet delay with a tight delay constraint in Fig. 8 and Fig. 10, respectively. The parameters of connections E', F', G', and H' are the same with connections E, F, G and H respectively, except the delay constraint. We changed from the loose delay constraint of 100 ms to a tight delay constraint of 30 ms. The simulation results still show that the LCST is 14% to 50% better than IEEE 802.16e and the E-LCST is 26% to 57% better than IEEE 802.16e in terms of the percentage of sleep periods. The average packet delay of the LCST is still the same as the IEEE 802.16e scheme, but the average packet delay in the E-LCST decreases obviously. This is because the value of delay constraint affects the length of sleep interval in type II connections. For type I connections, the E-LCST has 38% to 44% longer average packet delay than the IEEE 802.16e scheme. For type II connections, the E-LCST has 33% to 67% longer average packet delay than the IEEE 802.16e scheme. If the delay constraint is set smaller, the average packet delay in the E-LCST will become smaller. This is because we use the delay constraint to calculate the number of packets that can be grouped into a single frame for transmitting and thus to guarantee the QoS.

The listening windows of type II connections can transmit the MAC SDUs (service data units). If the size of a type II packet is smaller, the unused space in the listening window will be larger. In this situation, we can have higher probability to transmit type I packets within the type II listening window. Then the MSS will have more frames to enter the sleep mode. In Fig. 11, it shows the effect of packet size on the percentage of sleep periods. The A+E and C+E have more sleep periods than the A+G and C+G, respectively, because the packet size in connection E is smaller than that in connection G. The A+E also have a higher percentage of sleep periods than the C+E, because the packet size of A is smaller than that of C.

Note that the proposed two schemes were designed to piggyback the type I connection's traffic indication message at the type II connection's traffic indication message. If the number of type II connections is much less than type I connections, the percentage of sleep windows of our schemes will become smaller and the average delay may become longer. In the following, we will evaluate this situation. In Fig. 12, there is only one type II connection E in the following cases: A+E, A+B+E and

A+B+C+D+E. The average packet delay increases when the number of type I connections increases. This is because the total size of buffered packets is larger than the unused space that a listening window of type II can provide. The BS then has to transmit the unsent packets with another frame(s) and the packet delay becomes longer. In the case of A+B+C+D+E+F, there are two type II connections of equal packet size. Comparing between A+B+C+D+E and A+B+C+D+E+F, the average packet delay of the latter is smaller than the former, since the latter has more type II connections of equal packet size. Therefore, the proposed two schemes are suited to environments that allow type II connections to utilize its unused space in a frame to carry type I's packets.

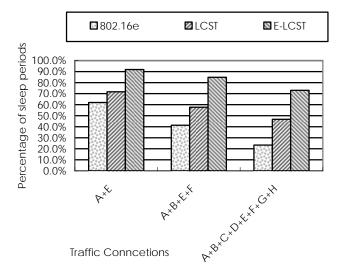


Fig. 7. Percentage of sleep periods under the loose delay constraint.

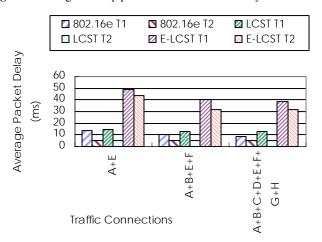


Fig. 8. Average packet delay under the loose delay constraint.

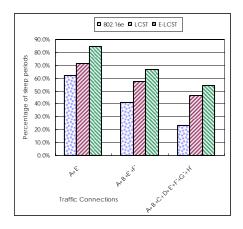


Fig. 9. Percentage of sleep periods under the tight delay constraint.

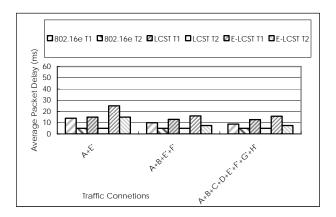


Fig. 10. Average packet delay under the tight delay constraint.

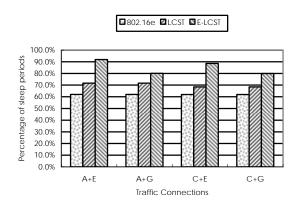


Fig. 11. The effect of packet size on percentage of sleep periods.

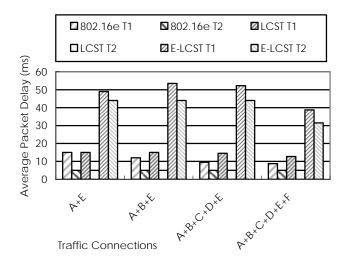


Fig. 12. The effect of number of type II connections on average packet delay.

5 Implementation Considerations

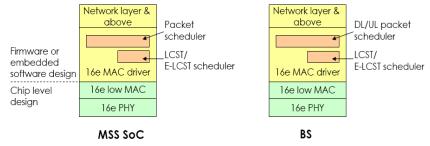


Fig. 13. Implementation of the proposed method on IEEE 802.16e SoC.

To implement the proposed method on an IEEE 802.16e system, firmware or embedded software for MSSs and BSs needs to be enhanced. Fig. 13 depicts a possible implementation of the proposed method on an IEEE 802.16e MSS SoC (System on Chip), and an IEEE 802.16e BS. The physical layer (PHY) and some time-critical MAC functions such as generating MAC header and packet encryption and integrity check are implemented in an ASIC chip. Management functions and high level MAC functions such as sleep mode operations are implemented in the embedded software or firmware depending on the architecture of the SoC. These functions control the SoC through an MAC driver. For the implementation of an MSS, the initial parameters of the sleep mode operation should be proposed by the LCST/E-LCST scheduler that sends a sleep mode request to the BS. The LCST or E-LCST

scheduler on the BS which received the request must perform the admission control based on the sleep mode response from the MSS and finally responds the request. The final sleep mode schedule is determined by the BS, and the parameters of the sleep mode operations derived by the LCST/E-LCST scheduling algorithm on both the MSS and BS must be synchronized. While an MSS has a packet to send, the packet scheduler on the MSS checks the LCST/E-LCST scheduler to determine the transmission slots so that the packet scheduler can transmit the packets in the minimal number of frames. On the other hand, if the BS has packets to send to the MSS, it also checks the LCST/E-LCST scheduler on the BS and schedules the packets.

6 Conclusions

We presented two efficient energy saving schemes for the sleep mode operations in IEEE 802.16e. The proposed schemes can minimize the listening windows of power saving classes of non-real-time packets (type I) and schedule real-time packets (type II) in less number of frames. The main idea of the proposed schemes is to reduce the number of listening windows for transmitting/receiving packets from all service connections, so that there is more common sleep time for the MSSs to enter the sleep mode and save more power. According to the simulation results, the LCST and E-LCST performed 14% to 50 % and 33% to 68% better than the IEEE 802.16e scheme, respectively, in terms of percentage of sleep periods. However, more packet delay is introduced by the proposed schemes. The LCST and E-LCST introduced 6% to 77% and 84% to 88% longer average packet delay for non-real-time packets than the IEEE 802.16e scheme, respectively. Nevertheless, the delay of each type II connection still met its delay constraint. In other words, the QoS requirements of type II connections in our proposed two schemes were still met. The proposed schemes are compatible with the conventional IEEE 802.16e standard, because we only need to adjust the parameter values of sleep mode operations of types I and II in the base station.

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