Enhanced Power Saving for IEEE 802.11 WLAN with Dynamic Slot Allocation*

Changsu Suh, Young-Bae Ko, and Jai-Hoon Kim

Graduate School of Information and Communication,
Ajou University, Republic of Korea
{scs, youngko, jaikim}@ajou.ac.kr

Abstract. In the area of wireless mobile communication, minimizing energy consumption as well as maximizing data throughput in medium access control (MAC) layer is a very important research issue. The Distributed Coordination Function (DCF) of IEEE 802.11 provides the power saving mechanism (PSM) that allows nodes to remain silent in 'doze mode' for reducing energy consumption. However, IEEE 802.11 PSM is known to cause unnecessary energy consumption due to the problems of an overhearing, a back-off time delay and possible packet collisions. To overcome these problems, we present a new MAC protocol called 'Slotted-PSM' for IEEE 802.11 WLANs. In our proposed scheme, the Beyond-ATIM window is divided into a number of time slots, and any node that participates in communication wakes up in its slot times only and other nodes can enter to doze mode during the slot times. Slotted-PSM can reduce unnecessary energy consumption and idle listening problem in the Beyond-ATIM window.

1 Introduction

Recently, there have been lots of attentions on developing energy efficient MAC protocols in wireless networks. These protocols are similar in the sense that they try to turn off their radio transceivers for reducing energy consumption whenever they are not involved in communication. Such a state of turning off is known as 'sleep' or 'doze' state. Neither a transmission nor a reception is allowed when a node stays in this inactive state, resulting in little energy consumption. The IEEE 802.11 DCF (Distributed Coordination Function) standard [9], the dominating WLAN technology today, also incorporates such a power saving mechanism (PSM) that uses awake and doze states. In 802.11 PSM, time is divided into beacon intervals and each node tries to synchronize with its neighbors to ensure that all nodes wake up at the same time. Any node can announce its

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pending data information during the period called the announcement traffic indication map (ATIM) window. During the period following ATIM window (we call this period as *Beyond-ATIM window*), nodes exchanging ATIM and ACK frames in the ATIM window period must remain in an awake state and perform data communication based on Carrier Sense Multiple Access with Coliision Avoidance (CSMA/CA) mechanism, whereas all other nodes go to 'doze state'. We are now arguing that, Beyond-ATIM window in the current 802.11 standard causes energy consumption with the following reasons:

Overhearing: A node may receive packets that are not destined for it. Unnecessarily receiving such packets will cause energy consumption.
Back-off time: A node in CSMA/CA is required to sense the medium in randomly chosen back-off time duration before sending any packets. During this time, node remains in awake state.
Packet collision: If two nodes transmit packets simultaneously, the packets are corrupted and the follow-on retransmission causes more energy consumption.

With respect to these problems, we propose a new energy efficient MAC protocol named "Slotted Power Saving Mechanism (i.e., Slotted-PSM)". Slotted-PSM divides the time of the Beyond-ATIM window period into equal slots of length L. When a node wants to send data packets, it first selects free slots which are not reserved by other nodes during the ATIM window, and then waits unless the slot time is not started in the Beyond-ATIM window. While waiting for its slot time, a node can enter to the doze mode for saving energy. Here, slots are allocated dynamically, and the allocated slot information will be piggybacked into legacy ATIM frame.

2 Related Works

Fig. 1 shows the basic PSM in DCF mode. As mentioned earlier, time in DCF is divided into beacon intervals. All nodes try to synchronize with each other by sending beacon frames and wake up at the beginning of every beacon interval. A beacon interval consists of two parts: ATIM window and Beyond-ATIM window. Generally, one ATIM window size is long enough to allow the transmission and retransmission of several ATIM packets [1,5]. In Fig. 1, nodes A, B and C intend to send data packet to node B, A and B respectively. So, during ATIM window, sender nodes announce the traffic information by sending an ATIM packet based on CSMA/CA mechanism (In Fig. 1, 'CS' means the carrier sensing after back-off time). A receiver node replies by sending an ATIM-ACK packet. A successful exchange of ATIM and ATIM-ACK packets between two nodes implies that both nodes continuously maintain awake mode for the data transmission after finishing ATIM window. However, other nodes (e.g., node D) are allowed to enter a doze mode until the next beacon interval. In the normal PSM in IEEE 802.11, ATIM window size as well as a beacon interval is fixed for synchronization between neighbor nodes. However, the fixed ATIM window critically

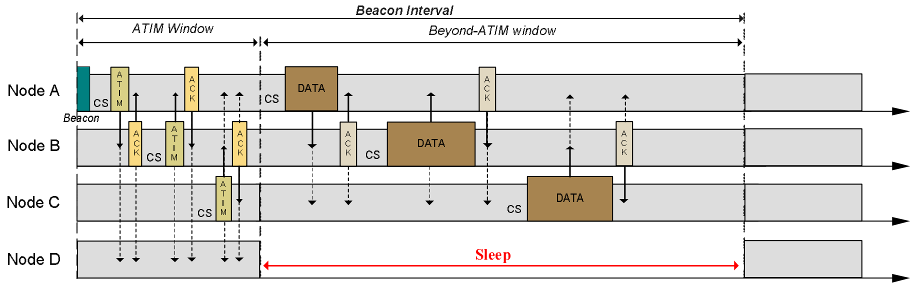


Fig. 1. The operation of basic PSM in IEEE 802.11 DCF

affects on throughput and energy consumption [1]. One of the previous research issues of the PSM IEEE 802.11 is to dynamically adjust the size of ATIM window. [2] proposes a mechanism to dynamically choose an ATIM window size for improving data throughput based on three indications. Generally, most of PSM schemes need the synchronization between neighbors, but it is difficult to achieve in a multi-hop, mobile ad hoc networking environment. However, [3] investigates three power management protocols based on IEEE 802.11 PSM scheme in unsynchronized multi-hop environments. [4] suggests three schemes for reducing the energy consumption in listening (1) by carrier sensing, (2) by dynamically re-size the ATIM window and (3) by scheduling wake-up times of sender and receiver based on past traffic patterns. [5] suggests scheme to enter sleep state early without being awake during the whole Beyond-ATIM window as well as to adjust the ATIM window size. [5] is able to reduce more energy consumption than normal PSM of IEEE 802.11 DCF, but it has some weakness that several nodes have to wait until other nodes finish data transmission despite of not participating in the communication and it has the hidden terminal problem in multi-hop environments.

3 Proposed Scheme

3.1 The Operation of Slotted-PSM

In our proposed scheme, we extend the Beyond-ATIM window to be divided into fixed time slots such that nodes can effectively use them for conserving energy. As each node bearing traffic reserves the time slot during ATIM-window period, it can exactly know when it needs to wake up for data communication. One whose slot has not yet arrived remains in the sleep state conserving additional energy. The operation of the Slotted-PSM mode is explained in detail by the following steps:

– At the starting of a new beacon interval, a node having data packets to send make a slot reservation. We perform this slot reservation as soon as back-off time is over and a node verifies that the wireless medium is free. After this,

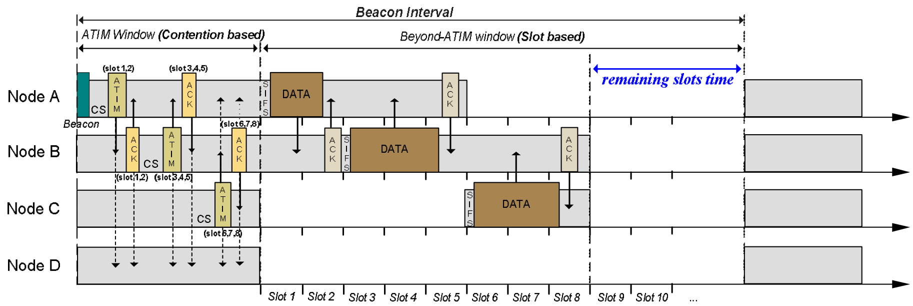


Fig. 2. The operation of Slotted-PSM

node transmits the ATIM packet piggybacked with the proposed list of slots required for the data transmission during the Beyond-ATIM window. To avoid overlapping during slot reservation, all nodes maintain the slot table that is updated every time the ATIM or ATIM-ACK is received. Slot table provides the information to the node about whether the slot is free or not. Note that, sender selects the slot based on amount of data traffic and the available slot table information.

– Actual slot reservation is performed after sender transmits the ATIM packet with proposed slot list to the target node as mentioned in the previous step. Here, we explain two different methods for reserving slots: (1) sender-initiated and (2) receiver-initiated. In (1), the slots for future data transmission are reserved by the sender side, which are same slots in the proposed slot list. However, it is possible that the same slots are already occupied by another sender(s) in the receiver. In this case, the receiver replies with ATIM-RE packet with free slot list to the sender. After receiving ATIM-RE packet, sender tries to re-selects the slots from the receiver's free slots and immediately sends a new ATIM packet. In (2), slots are reserved at the receiver side. Sender transmits ATIM packet with free slot list (proposed slot list) to the receiver. The receiver then chooses the appropriate slot by considering its slot table and sender's free slot list. After this, it replies the ATIM-ACK with the selected slots back to sender. In this case, nodes around the sender may not receive the ATIM-ACK and may remain unaware of the used slots. Therefore, after receiving ATIM-ACK, senders need to send another packet for announcing the occupied slots. Since this can cause more overhead, we have used the first method for slot reservation in our implementation.
– After the ATIM window phase is over, each sender transmits data according to the reserved slots. Other nodes maintain doze state and only wake up at the beginning of their slots. With the starting of the new beacon interval, all slots are reset and each node tries to reserve new slots for further data transmission.

Fig. 2 illustrates our scheme ((1) sender-initiated). Each node selects its slots for future data transmission based on its empty slot table. Slot 1 and 2 are reserved by node A for sending its data to node B. Slot 3, 4 and 5 are reserved by node B for its data transmission. So both nodes will have to maintain awake state from slot 1 to 5. After slot 5, node A enters to doze state but node B still maintain awake state to receive data from node C at slot 6, 7 and 8. Hence, we see that any node without a reserved slot or after completing its data communication may go into sleep state conserving energy. Moreover, the possibility of collision is reduced as the packets are sent only in the reserved slot. Reduction in collision leads to increase in data throughput. Therefore, using our scheme, we expect to not only save energy but also increase throughput.

3.2 Collision, Hidden Terminal Problem and Synchronization in Slotted-PSM

In order to avoid a data packet collision by newly joined nodes, a sender in slotted-PSM waits for the SIFS time interval before transmitting its data. Nevertheless, the data collision problem in the Beyond-ATIM window continuously remains due to long range of carrier sensing [10] or interference from other devices. If the nodes do not finish the communication in their reserved slot time, they uses remaining slot time (refer to Fig.2). The remaining slot time is some extra time in the Beyond-ATIM window after all reserved slots become over. Any data communication that occurs in this time is based on CSMA/CA mechanism. Additionally, our scheme also prohibits the hidden terminal problem during data communication in the Beyond-ATIM window phase. In IEEE 802.11 and other related protocols this problem is handled by RTS/CTS mechanism. In Slotted-PSM, since sender knows the reserved slot information of other senders through ATIM/ATIM-ACK packets and simultaneous data transmission never occurs, it avoids the hidden terminal problem without the overhead of RTS/CTS exchanging. Finally we have assumed that the synchronization is achieved through beacon packet or out-of-band solutions such as GPS [12]. All nodes wake up at the same time for exchanging the ATIM and ATIM-ACK packets. If out-of-band solution is used, synchronization is perfect and there will be no other overhead. However, by using beacon packet solution, a perfect synchronization is not guaranteed in multi-hop environments. To improve the performance, our scheme has to be combined with some synchronization mechanism. However, developing a scheme for synchronization is outside the scope of this paper.

3.3 Energy Saving Analysis

Since the primary goal of our scheme is to reduce energy consumption as compared to the IEEE 802.11 PSM, we present the mathematical analysis on saving energy. We can express the total energy consumed by a node for a beacon interval T as equation (1).

$$E_{node} = E_{ATIM} + E_{BeyondATIM} \tag{1}$$

E_{ATIM} and $E_{BeyondATIM}$ mean the energy consumption during the ATIM window and Beyond-ATIM window period. Equation (2) shows the energy consumption during the ATIM window in more detail. In this equation, E_{beacon} is the energy consumed while transmitting or receiving beacon packet and $E_{ctrlpkt}$ is a combination of the transmitted and received power for exchanging ATIM and ATIM-ACK packets. During the remaining ATIM window (T_{ATIM} - T_{beacon} - $T_{ctrlpkt}$), a node stays in the idle mode and consumes P_{idle} energy. In the ATIM window, the operations for both Slotted-PSM and basic PSM are the same, and its equation is expressed to

$$E_{ATIM} = E_{beacon} + E_{ctrlpkt} + P_{idle} \cdot (T_{ATIM} - T_{beacon} - T_{ctrlpkt}) \quad (2)$$

Equation (3) is only valid for the nodes that do not perform data communication during the Beyond ATIM-window. Here, T_{Beyond} is the time interval for the Beyond-ATIM window.

$$E^{sleep\_node}_{Beyond} = P_{sleep} \cdot T_{Beyond} \quad (3)$$

In the Beyond-ATIM window, both schemes have different operations and accordingly different energy consumption. Basic PSM's energy consumption is given by (4). In this equation, P_{rx} and P_{tx} mean the energy for transmitting and receiving data packets. T_{rx_data} and T_{tx_data} are times required for receiving and transmitting. During the remaining Beyond-ATIM window (T_{Beyond} - T_{rx_data} - T_{tx_data}), a node stays in the idle mode and consumes P_{idle} energy.

$$\begin{aligned} E^{Basic}_{Beyond} &= P_{rx} \cdot T_{rx\_data} + P_{tx} \cdot T_{tx\_data} \\ &+ P_{idle} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data}) \end{aligned} \quad (4)$$

Equation (5) shows the energy consumption of Slotted-PSM in the Beyond-ATIM window. For simplifying analysis, we omit the benefit of our scheme such as eliminating RTS/CTS overhead and back-off time in T_{rx_data} and T_{tx_data}. The main difference between (4) and (5) is that Slotted-PSM's node stays in the idle mode during only T_{idle_slot} and then it can stay in sleep mode during the rest time except in T_{idle_slot}, T_{rx_data} and T_{tx_data}.

$$\begin{aligned} E^{Slotted}_{Beyond} &= P_{rx} \cdot T_{rx\_data} + P_{tx} \cdot T_{tx\_data} + P_{idle} \cdot T_{idle\_slot} \\ &+ P_{sleep} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data} - T_{idle\_slot}) \end{aligned} \quad (5)$$

T_{idle_slot} means the remained times except to T_{rx_data} or T_{tx_data} in *reserved slots*, which is expressed in (6). In this equation, T_{one_slot} is the length of a slot. In Slotted-ATIM, communication nodes try to reserve the enough slots for transmitting data packets. Therefore, generally, transmission time may be not fixed with reserved slot times. In this case, T_{idle_slot} is generated.

$$\begin{aligned} T_{idle\_slot} &= (\left\lceil \frac{T_{rx\_data}}{T_{one\_slot}} \right\rceil \cdot T_{one\_slot} - T_{rx\_data}) \\ &+ (\left\lceil \frac{T_{tx\_data}}{T_{one\_slot}} \right\rceil \cdot T_{one\_slot} - T_{tx\_data}) \end{aligned} \quad (6)$$

The benefit in terms of energy obtained by using Slotted-PSM is the difference between (4) and (5). By ignoring the minute power of the sleep state because its energy consumption is much smaller than Tx state or Rx state, we can approximate the benefit of Slotted-PSM as (7):

$$\begin{aligned}\Delta E_{node} &= E_{node}^{Basic} - E_{node}^{Slotted} = E_{Beyond}^{Basic} - E_{Beyond}^{Slotted} \\ &= P_{idle} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data}) - P_{idle} \cdot T_{idle\_slot} \\ &\quad - P_{sleep} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data} - T_{idle\_slot}) \\ &\approx P_{idle} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data}) - P_{idle} \cdot T_{idle\_slot} \end{aligned} \quad (7)$$

If T_{one_slot} can divide T_{rx_data} and T_{tx_data} without remainder, T_{idle_slot} becomes zero in (6). In this case, the performance of Slotted-PSM is highest and equation (7) can be described to (8).

$$Max(\Delta E_{node}) = P_{idle} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data}) \quad (8)$$

Eventually, the maximum energy benefit of Slotted-PSM comparing to basic PSM can be defined as $P_{idle} \cdot (T_{Beyond} - T_{rx\_data} - T_{tx\_data})$. Hence, our scheme shows the significant energy conservation which is crucial for the wireless mobile devices that are operated using limited power sources.

4 Performance Evaluations

4.1 Simulation Environments

In our simulation, we modified the CMU extended version of ns-2 [11]. We have assumed the maximum bit rate of 1Mbps, the transmission range for each node to be approximately 250m and packet size fixed at 512 bytes. For calculating energy consumption of two protocols, we use 1.65W, 1.4W and 0.045W as value of power consumed by the MAC layer while transmitting, receiving and in doze state [8]. We have set beacon interval to 100ms and ATIM window to 20ms as in [2, 4]. We fix the ATIM window size and have not considered adjusting the size of ATIM window scheme. Each simulation is performed for 50 seconds in a wireless LAN environment, in which all nodes are within each other's transmission range and every source node can reach its destination in a single hop. Analysis of the performance evaluation is for the two scenarios. In the first scenario, data traffic is changed from high traffic to low traffic in 16 nodes. In the second scenario, we focus on throughput of both protocols in the high data traffic given 30 nodes. Both scenarios are for the wireless LAN environment [2,4]. Half of the nodes are sources and rests are destinations. One of the important issues in our scheme is to decide the optimal size of a slot. If the size of a slot is larger than the period for DATA/ACK transmission, it causes unnecessary time after data transmission is finished within the reserved slot. Otherwise, if the size of a slot is small, many number of slots causes the problems such as complexity of slot scheduling and large size of ATIM packet. Fig. 3 shows the average energy consumption of Slotted-PSM with the increasing slot size in various message inter-arrival times. The message inter-arrival time affects amount of data traffic in the simulation. As shown in Fig. 3, a reasonable slot size for Slotted-PSM is 2.6ms. Therefore, the comparison of our scheme with Basic-PSM is performed with slot size equal to 2.6ms.

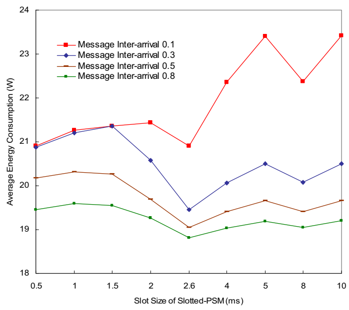
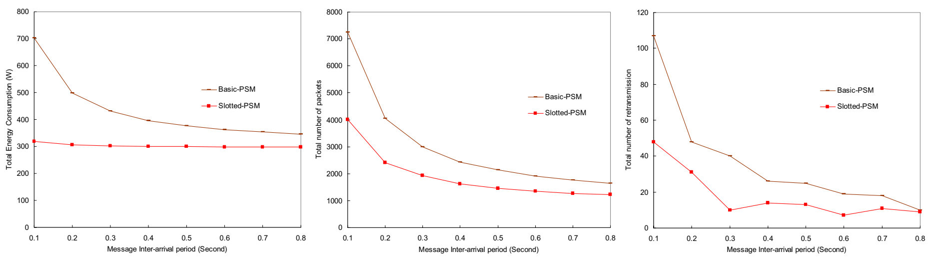


Fig. 3. Average energy consumption according to the slot size

4.2 Simulation Results

Fig. 4(a) shows the total energy consumption as the message inter-arrival period is increased. According to the graph, Slotted-PSM consumes less energy than other protocol as the network load is increased . The reason is that, Slotted-PSM does not spend the unnecessary energy consumption for data transmission, but the basic PSM consumes more energy due to overhearing, waiting for back-off time and packet collisions. Therefore, the energy saving performance of Slotted-PSM is better in situation where data packets are frequently transmitted.

Fig. 4(b) shows the total number of packets (i.e. Beacon, ATIM, ATIM-ACK, RTS, CTS, DATA and ACK) which are generated during simulation time. In our scheme, when data packet is transmitted in reserved slots, RTS and CTS packets are not necessary (we mentioned this fact in the section 3). So RTS or CTS packet is not sent and counted in Slotted-PSM. Therefore, total number of packets of our proposed scheme is smaller than that of Basic-PSM. Fig. 4(c) shows the total number of retransmission by packet collision and loss. Our scheme can reduce the data collision in Beyond-ATIM window because each node should try to transmit its data packet only in its reserved slot time. Therefore, total retransmissions in Slotted-PSM are counted smaller than Basic-PSM.



(a) (b) (c)

Fig. 4. Comparison of Slotted-PSM to Basic Basic-PSM with a variation of *traffic loads* :(a)Total Energy Consumption, (b)Total number of packets and (c)Total number of retransmission

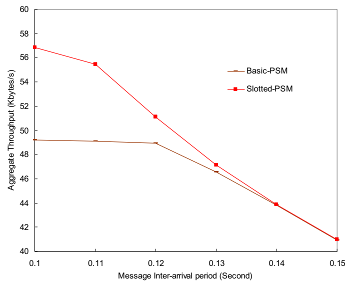
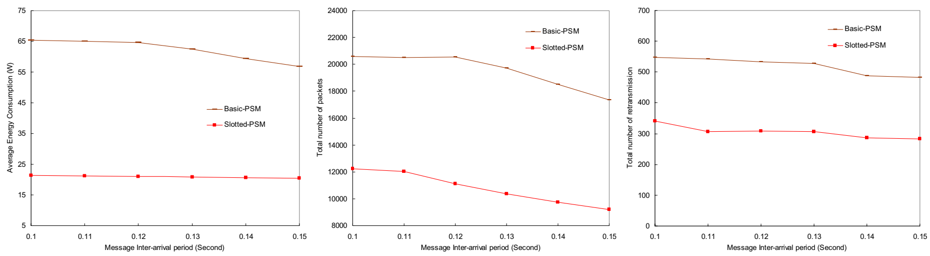


Fig. 5. Aggregate throughput (Kbytes/s) in the high data traffics



(a) (b) (c)

Fig. 6. Comparison of Slotted-PSM to Basic Basic-PSM in the high data traffics :(a)Total Energy Consumption, (b)Total number of packets and (c)Total number of retransmission

Fig. 5 and 6 are the results of the second scenario in the high data traffic environments (30 nodes). In this scenario, we focus more on the analyzing the aggregate throughput of both protocols. As mentioned above, our scheme can reduce the RTS/CTS overhead and the data collision problem. These characteristics may lead to increase of data throughput. Fig. 5 shows the aggregate throughput (Kbytes/s) of both protocols, and the result shows that the aggregate throughput of Slotted-PSM is larger than Basic-PSM. The throughput performance of Slotted-PSM is better in situation where data packets are frequently transmitted because high data traffic causes lots of RTS/CTS overhead and packet collision in Basic-PSM. Other Fig. 6 shows the results of energy consumption, total number of packets and total number of retransmission in the high traffics environment. Through these figures, our proposed scheme can expect to not only save energy but also increase throughput more than Basic-PSM.

5 Conclusions

In this paper, we proposed the energy efficient slot based MAC protocol for IEEE 802.11 wireless LANs, named the Slotted-PSM (Slotted Power Saving Mechanism). To solve the problem of unnecessary energy consumption due to

CSMA/CA scheme, Slotted-PSM divides Beyond-ATIM window into several slots, and allows the node which participates in communication wakes up only in its slot times. We believe that our scheme can effectively save the energy of communication as well as increase data throughput. We verified our scheme's effectiveness by performance evaluation, and made very positive results of saving 70% energy in our Slotted-PSM compared to the IEEE 802.11 PSM.

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