Load-Aware Power Saving Mechanism in WLAN

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Abstract—In Wireless Local Area Networks (WLANs), the power saving mechanism for Distributed Coordination Function (DCF) allows stations (STAs) to periodically wake up and check the existence of buffered packets in the Access Point (AP). If notified by the beacon of buffered packet’s presence, an STA contends for sending the PS-Poll to the AP which will respond with the corresponding buffered packet either 1) immediately (Immediate-Send), or 2) at a later time (Later-Send). IEEE 802.11 standard does not specify the detailed scheme of Later-Send and most current mechanisms adopt Immediate-Send. Though Immediate-Send performs well under light load condition, it is inefficient under heavy load condition because of the existence of some STAs contending throughout the whole beacon interval at the price of corresponding power consumption but getting no access opportunity, which degrades the power saving performance of both total power consumption and energy efficiency, i.e. the average power consumed for one unit of payload. We propose and analyze a load aware power saving mechanism (LAPS) that uses Immediate-Send under light load condition and uses a proposed detailed mechanism of Later-Send under heavy load condition. The threshold to divide light and heavy load is also calculated. Numerical results show the effectiveness of our mechanism.

Keywords- Power Saving, IEEE 802.11, WLAN

I. INTRODUCTION

Stations (STAs) in Wireless Local Area Networks (WLANs) are mainly portable devices powered by limited batteries and the life time is a critical limiting operational factor. Therefore, it is important to reduce power consumption of wireless hosts in order to prolong the operation time.

In the past few years, power saving (PS) has been a research focus and a number of mechanisms have been proposed. These mechanisms operate in different networks, including Wireless LAN [2-8], Wireless Sensor Network [11]-[12], and IEEE 802.16e Wireless MAN [9]-[10]. PS schemes are also investigated at different layers of the protocol stack, including Medium Access Control (MAC) layer [2]-[10], routing layer [13]-[14], and transport layer [15]. In addition, these mechanisms can be divided according to saved power’s usage. When awake, STAs consume power for transmitting, receiving, and just being idle. [17] proposes a power control based mechanism to save transmitting power. Instead of connecting directly to the base station, a mobile station running on low battery can adopt a relay structure, use a nearby mobile station to forward its call and save transmitting power [18]. In IEEE 802.11 standard, a sleep based PS mechanism is adopted to save power consumed on being awake and idle by introducing a doze state and putting the wireless interface in the doze state when reasonable. This paper focuses on the sleep based PS mechanism at MAC layer in WLAN.

In an infrastructure network, the access point (AP) buffers packets towards stations in power saving mode (PS-STAs) and informs them the corresponding buffer status through traffic indication map (TIM) included as an element within all beacons generated by the AP. With listen interval (LI) generally the same as beacon interval (BI), a PS-STA periodically wakes up to listen for the beacon and determines the existence of its buffered packet in the AP. If the packet exists, the STA will contend for sending a PS-Poll frame to request for its packet, otherwise it will transit to doze state to save power. Hereafter, we call such PS-STAs that have buffered packets in the AP “Awake-STAs”.

In PS mode, an STA’s wireless interface has two different power states: awake and doze, and we may say that an STA is in a certain state, when its wireless interface is in that state. The STA in awake state consumes much more power than in doze state [16] and stays in one of the three different statuses: idle, receiving and transmitting.

The classification of different STAs, states, and statuses are shown in Fig. 1.

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**Fig. 1** STAs, states, and statuses in IEEE 802.11 PS scheme

Upon receiving a PS-Poll, the AP will either respond with the corresponding buffered packet immediately, or acknowledge the PS-Poll first and send the packet at a later time [1]. Hereafter, we call the former method “Immediate-Send” and the latter “Later-Send”. Both how to choose from the two different methods and Later-Send mechanism’s detailed algorithm are out of the scope of the standard and left up to the manufactures.

Since IEEE 802.11 standard only provides the base of sleep mode mechanism, there is room for the enhancement. By optimizing the timing and duration of doze state, [7] proposes an adaptive algorithm with the objective of minimizing power consumption with respect to a QoS constraint namely average packet delay. [5] proposes a hybrid polling scheme that is
suitable for the current Internet environment in which traffic is generally bursty due to various applications such as FTP and HTTP. [3] takes the difference of STAs’ remaining power into consideration and proposes a priority based scheme in which STAs transmit PS-Polls according to their remaining power so that the power of all STAs are consumed uniformly. [8] adjusts the L1 to optimize STAs’ lifetime while maintaining the link quality in terms of frame loss and delay. An “arranged PS scheme” which reduces the number of collisions by avoiding the transmissions of redundant control packets and then enhances the system throughput is proposed in [6]. [4] proposes a double-buffering mechanism by considering the existence of broadcast and multicast services.

This paper focuses on the effect of the choice between the AP’s two responding methods on the sleep based power saving mechanism’s performance of both total power consumption and energy efficiency, i.e. the average power consumed for one unit of payload. The remainder is organized as follows. In Section II, Immediate-Send mechanism’s performances under different load conditions are analyzed. In Section III, we propose and analyze LAPS that combines Immediate-Send and “Polling First, Data Later” (PFDL) which is a proposed detailed scheme belonging to Later-Send method. The performance of our mechanism is evaluated in section IV. Finally, we conclude our paper in Section V.

II. IMMEDIATE-SEND MECHANISM

In this section, Immediate-Send mechanism’s power saving performance is analyzed. The analysis includes three parts. In the first part, the assumptions we made are listed. In the second part, we demonstrate that Immediate-Send has the best performance of total power consumption and energy efficiency when the load at the AP is light and all Awake-STAs can be served in this BI. Immediate-Send’s ineffectiveness under heavy load condition is analyzed in the third part.

A. Assumptions

The assumptions below will simplify the analysis in section II and III, however they are not necessary for the correct and efficient operation of our proposed mechanism.

Similar to that in [3]-[4], we do not consider the channel propagation delay, assume only downlink data traffic, i.e., no data traffic from STAs to the AP, and the same packet length. We also assume a perfect physical wireless channel without wireless transmission error and fading.

If there exists more than one Awake-STA, they will contend with each other to transmit the PS-Polls. Such contention not only results in PS-Polls’ transmission order, but also brings collisions and additional waiting time which is the time spent by all Awake-STAs to decrease their contention windows (CWs). This paper, however, considers a perfect MAC without collision and additional waiting time except DIFS and SIFS since: 1) this paper focuses on the impact of PS-Polls and data packets’ transmission order on the power saving performance 2) with Awake-STAs having their original CW being CW_{min}[1], the additional time is limited.

B. Power saving performance under light load condition

Let n denote the number of all stations including m Awake-STAs to send PS-Polls and (n-m) stations that will directly transit to doze state after the beacon. The Immediate-Send mechanism is shown in Fig. 2, where m denotes the number of Awake-STAs and u denotes the maximal number of STAs that can be served in this BI. Note that with this mechanism, there are (m-u) stations waiting through the whole BI to try to send their PS-Polls and transiting to doze state at the end of this BI. The subscript “0”, “1” and “u-1” denote the first, second, and last Awake-STA that has sent its PS-Poll in this BI rather than three particular Awake-STAs.

![Fig. 2 The Immediate-Send Mechanism (without collision and additional waiting time)](image)

Let S_i denote STA_i, and BI denote the length of BI. We use T_{awake,i} to denote the power consumption of S_i, and T_{awake,IS} to denote the total power consumption of all n STAs in the system in a BI with the Immediate-Send mechanism.

We use X to denote the set of all STAs and Y to denote the set of Awake-STAs. Let \( X = \{x \in Z \mid 0 \leq x \leq n-1 \} \) , and \( Y = \{y_i \mid y_i \in X, 0 \leq i \leq m-1 \} \). Since the (n-m) stations with no data buffered in the AP transit to doze state after receiving the beacon and hence consume much less power than the other m stations, we ignore their power consumption and compute the total power consumption as

\[
T_{awake,IS} = \sum_{x \in X} T_{awake,i} = \sum_{x \in Y} T_{awake,i} + \sum_{x \in Y} T_{awake,i} = \sum_{i=0}^{u-1} T_{awake,i}. \tag{1}
\]

In one BI, an Awake-STA keeps awake from the start of the beacon and until it transits to doze state either due to having sent the PS-Poll and received its data or due to the beacon interval ending. In the awake duration, an Awake-STA may stay in idle, receiving, and transmitting statuses with different power consumption rate. For example, the Lucent IEEE 802.11 WaveLan PC Card consumes 0.74W, 0.9W, and 1.4W in idle, receiving, and transmitting statuses respectively [16]. So the power consumption of an Awake-STA in one BI should be the weighted sum of the three statuses’ time durations. However, since the power consumption rates of idle and receiving statuses are close and Awake-STAs’ transmitting durations are determined by a limited number of PS-Polls, the sum of the three statuses’ time durations, i.e. the awake duration, can be used to approximate the power consumption.

Let L_{PS-Poll}, L_0, L_{ACK} and L_2 denote the packet durations of a PS-Poll, a data packet, an ACK and the beacon. Without loss of
generality, it is assumed that $y_0$ is first served, $y_1$ is the second, and so on.

If $m \leq u$, all Awake-STAs will have opportunities to send PS-Polls and receive their data with this BI. So we have

$$T_{\text{awake,IS}} = \sum_{i=1}^{n} T_{\text{awake,IS}, i} = \sum_{j=0}^{m-1} T_{\text{awake,IS}, j} + T_{\text{awake,IS}, j} + \sum_{j=0}^{m-1} T_{\text{awake,IS}, j}$$

$$= (L_{\text{PS-Poll}} + L_D + L_{\text{ACK}} + DIFS + 2SIFS) + 2T_{\text{awake,IS}, 0} + \sum_{j=2}^{m} T_{\text{awake,IS}, j}.$$  \hspace{1cm} (2)

Assuming no additional waiting time, we have

$$T_{\text{awake,IS}} = L_B + L_{\text{PS-Poll}} + L_D + L_{\text{ACK}} + DIFS + 2SIFS.$$  \hspace{1cm} (3)

Let $L_y = L_{\text{PS-Poll}} + L_D + L_{\text{ACK}} + DIFS + 2SIFS$, then equation (2) rewrites as

$$T_{\text{awake,IS}} \geq m(m-1)L_y / 2 + mT_{\text{awake,IS}}.$$  \hspace{1cm} (4)

$$= mL_y + m(m+1)L_y / 2.$$  \hspace{1cm} (5)

In equation (4), the equal is obtained when the Immediate-Send mechanism is used. Therefore, this mechanism has the best performance of total power consumption when the load at the AP is light and all Awake-STAs can be served in one BI. As all Awake-STAs are served, this mechanism also has the best performance of energy efficiency.

The relation between $u$ and $B$ can be expressed as

$$B = L_B + Lu.$$  \hspace{1cm} (5)

Since $u$ is an integer, we have

$$u = \left(\left\lfloor BI \right\rfloor - L_B \right) / L_u.$$  \hspace{1cm} (6)

C. Power saving performance under heavy load condition

The most important difference between the two load conditions is: when $m > u$, there are $(m-u)$ STAs waiting and “wasting” for the whole BI to try to send PS-Polls, as depicted in Fig. 2, while when $m \leq u$, all the time spent by the $m$ STAs is worthwhile since sooner or later all the Awake-STAs send PS-Polls and receive data.

Under heavy load condition, we have

$$T_{\text{awake,IS}} = \sum_{i=1}^{n} T_{\text{awake,IS}} = \sum_{j=0}^{m-1} T_{\text{awake,IS}, j} + \sum_{j=0}^{m-1} T_{\text{awake,IS}, j}.$$  \hspace{1cm} (7)

Let $T_{\text{success}} = \sum_{j=0}^{m-1} T_{\text{awake,IS}, j}$, where “success” means that these $u$ STAs send their PS-Polls and receiving data. Similarly, let $T_{\text{failure}} = \sum_{j=m}^{n-1} T_{\text{awake,IS}, j}$, where “failure” means that these $(m-u)$ STAs do not send their PS-Polls.

With equation (4), we have

$$T_{\text{success}} = uL_y + u(u+1)L_y / 2.$$  \hspace{1cm} (8)

$T_{\text{failure}}$ can be calculated as

$$T_{\text{failure}} = (m-u)BI.$$  \hspace{1cm} (9)

By substituting (8) (9) into (7), we have

$$T_{\text{awake,IS}} = uL_y + u(u+1)L_y / 2 + (m-u)BI.$$  \hspace{1cm} (10)

With (4) and (10), the power consumption under different load conditions is

$$T_{\text{awake,IS}} = \begin{cases} mL_y + m(m+1)L_y / 2 & m \leq u \\ mL_y + u(u+1)L_y / 2 + BI(m-u) / u & m \geq u + 1. \end{cases}$$  \hspace{1cm} (11)

Energy efficiency is defined as the power consumed for one unit of payload. In the whole procedure of retrieving a packet from the AP, since the same packet length is assumed, the overhead of MAC and Physical Layer (PHY) headers, PS-Polls and ACKs, DIFS and SIFS is constant. In addition, Awake-STAs’ total awake duration is used to denote the total power consumption. So the average awake duration for receiving a packet is used to represent the Awake-STAs’ energy efficiency.

Let $\eta_{IS}$ denote the energy efficiency for the Immediate-Send mechanism. With (11), $\eta_{IS}$ can be obtained as

$$\eta_{IS} = \begin{cases} L_y + u(m+1)L_y / 2 & m \leq u \\ L_y + u(u+1)L_y / 2 + BI(m-u) / u & m \geq u + 1. \end{cases}$$  \hspace{1cm} (12)

Since $BI$ is constant and $u$ is a fixed number, it can be seen from (11) and (12) that when $m > u$, the power consumption and energy efficiency values both increase linearly at the rate of $BI$ with $m$.

III. LOAD-AWARE POWER SAVING MECHANISM

In this section, we first propose the LAPS mechanism that uses the Immediate-Send mechanism under light load condition and a proposed PFDL mechanism belonging to the Later-Send method under heavy load condition. Then, PFDL is presented and demonstrated through analysis to have better performance than Immediate-Send under heavy load condition. The threshold $Q_h$ of heavy load is also calculated.

In order to solve Immediate-Send’s ineffectiveness under heavy load condition, LAPS lets the AP compute the sum of all buffered packets at the time just before sending beacons. Then the AP compares the computed load with $Q_h$ to determine whether the load is light or heavy and chooses accordingly the appropriate mechanism from Immediate-Send and PFDL. All STAs are notified about the choice by the beacon, and then the Awake-STAs adopt the right mechanism. The flow chart of LAPS is shown in Fig. 3.

PFDL is shown in Fig. 4. In this mechanism, BI is divided into two phases: the polling phase and data phase. In the polling phase, PS-Polls are transmitted and the AP keeps on receiving PS-Polls and replying with ACKs but no data. Let $v$ denote the maximal number of STAs that can be served in a BI when using PFDL. Note that $v$ is smaller than $u$ because PFDL uses more control packets than Immediate-Send. When the AP observes that the number of already received PS-Polls is $v$, it replies to the $(v-1)_{th}$ PS-Poll with an special ACK in which the information of “Stop polling phase and start data phase” is piggybacked by one bit. On receiving the notification, all the Awake-STAs not having sent their PS-Polls will transit to doze state to avoid unnecessary power consumption in the data phase in which the AP transmits data successively to STAs having sent PS-Polls.
Let $T_p$ denote the time duration of the polling phase. For PFDL, when $m > v$, Awake-STAs' total power consumption $T_{wake,PFDL}$ can be calculated as

$$T_{wake,PFDL} = \sum_{j=0}^{m-1} T_{wake,j} = \sum_{j=0}^{m-1} \frac{T_p v (v+1/2) m L_{ACK}}{2} + \frac{v(m+v+1)SIFS + v(v+1+2m)L_{ACK}}{2}$$

where the values of $m$, $v$, are fixed values, it can be seen from (13) that when $m > v$, the overall power consumption increases linearly at the rate $T_p$ with $m$. Since the power consumption of PFDL and Immediate-Send both increase linearly but with the increasing rate's gap of $(BI-T_p)$, the power consumption of these two mechanisms are quite different.

By substituting (14) into (13), we have

$$T_{wake,PFDL} = mL_v + mv(DIFS + L_{PS-Poll} + SIFS + L_{ACK}) + \frac{v(m+v+1)SIFS + v(v+1+2m)L_{ACK}}{2}$$

Let $\Delta T_{wake}$ denote the difference between Immediate-Send and PFDL's power consumption under heavy load condition. With (11) and (15), we have

$$\Delta T_{wake} = [mL_v + u(u+1)L_s / 2 + (m-u) BI]$$

$$- [mL_v + mv(DIFS + L_{PS-Poll}) + L_v v(v+1)/2 + \frac{v(m+v+1)SIFS + v(v+1+2m)L_{ACK}}{2}]$$

When $\Delta T_{wake} = 0$, we have the solution $m_0$ as

$$m_0 = \frac{Lu_v + u(u+1) L_s / 2 + (m-u) BI}{2 + v(m+v+1)SIFS + v(v+1+2m)L_{ACK}}$$

For PFDL, the relation between $v$ and $BI$ can be expressed as

$$BI = L_v + (DIFS + L_{PS-Poll} + SIFS + L_{ACK})v$$

So we have $v$ as

$$v = \frac{(BI - L_v)}{(L_s + SIFS + L_{ACK})}.$$  \hspace{1cm} (19)

With (5) and (18), the ration between $u$ and $v$ can be expressed as

$$u / v = (L_{v} + SIFS + L_{ACK}) / L_{s}. \hspace{1cm} (20)$$

By substituting (6), (19) and (20) into (17), we have

$$m = \frac{BL - L_v + L_s + SIFS + L_{ACK}}{2L_v + L_s + 2SIFS + L_{ACK}}L_v + (L_v + SIFS + L_{ACK}) / (BL - L_v)$$

As $Q_a$ is the threshold, $Q_{th}$ equals to $m_0$. Let $Q_a$ be an integer, and we have

$$Q_a = \lfloor m_0 \rfloor. \hspace{1cm} (22)$$

With (11) and (15), since $Q_a > u \geq v$, the power consumption of LAPS can be expressed as

$$T_{wake,LAPS} = \frac{mL_v + m(m+1)L_s / 2}{uL_v + u(u+1)L_s / 2 + (m-u) BI} \hspace{1cm} m \leq u$$

$$mL_v + mv(DIFS + L_{PS-Poll}) + L_v v(v+1)/2 + m \geq Q_a$$

where the values of $u$, $v$ and $Q_a$ are in (6), (19) and (22).

Let $\eta_{LAPS}$ denote the energy efficiency for LAPS. With (23), $\eta_{LAPS}$ can be obtained as

$$\eta_{LAPS} = \frac{L_s + (m+1)L_v / 2}{uL_v + u(u+1)L_s / 2 + BI(m-u) / u} \hspace{1cm} u + 1 \leq m \leq Q_{th}$$

$$mL_v + mv(DIFS + L_{PS-Poll}) + L_v v(v+1)/2 + m \geq Q_a$$

$$\frac{mL_v + mv(DIFS + L_{PS-Poll}) + L_v v(v+1) / 2 + m \geq Q_a}{(m+v+1)SIFS + v(v+1+2m)L_{ACK} / 2} \hspace{1cm} (24)$$

### IV. Numerical Results

The model and computation in previous sections are used to evaluate the proposed LAPS mechanism. The parameters in the evaluation follow the standard [1] for DSSS PHY and are listed in Table 1.

<table>
<thead>
<tr>
<th>MAC header</th>
<th>224 bits</th>
<th>Channel bit rate</th>
<th>2 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY header</td>
<td>192 bits</td>
<td>Basic bit rate</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Beacon packet</td>
<td>200 bytes</td>
<td>SIFS</td>
<td>10 us</td>
</tr>
<tr>
<td>PS-Poll</td>
<td>160 bits</td>
<td>PHY header</td>
<td>50 us</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bits</td>
<td>Beacon interval</td>
<td>100 ms</td>
</tr>
</tbody>
</table>

Table 1 System parameters for evaluation
In the following figures, power consumption is represented by awake duration and the metric is millisecond, as explained in section II.

Fig. 5 shows the total power consumption for Immediate-Send and LAPS mechanisms in one BI with different data packet sizes. When Awake-STAs’ number is below the threshold $Q_{th}$, LAPS in Fig. 3 is the same as Immediate-Send mechanism, which is the reason of the curves’ superposition in Figs. 5 and 6. After $Q_{th}$, the curves fork and LAPS obtains better performance than Immediate-Send. For Immediate-Send, power consumption increases linearly after $Q_{th}$ at the rate of BI per STA since only some Awake-STAs can be served in this BI and the other Awake-STAs will keep on waiting and wasting power for the time duration of a whole BI. For LAPS, as the stations not served in this BI only wait in the polling phase, the overall power consumption increases linearly at the rate of the polling phase’s duration per STA.

Comparing the curves of different data packet sizes, it can be seen that the relative advantage of LAPS over Immediate-Send mechanism decreases with the packet size because the smaller size leads to the corresponding larger overhead of the control packets in polling phase. With the smaller packet size, $Q_{th}$ is larger since more packets can be served in one BI. For Immediate-Send, power consumption decreases with the packet size because of less STAs that are not served. For LAPS, however, power consumption increases with the packet size because more STAs that can be served and fewer STAs that transit to doze state at the end of the polling phase.

![Fig. 5 Comparison of power consumption](image)

Fig. 5 Comparison of power consumption

Fig. 6 illustrates the comparison of energy efficiency represented by the average awake duration for the payload of 1024 bytes. Similar to the result of power consumption, energy efficiency’s increasing rate of Immediate-Send is higher than LAPS after the $Q_{th}$ because LAPS avoids the power consumed by STAs not served. It can also be seen that LAPS has better performance with larger data packet size since the overhead is smaller.

![Fig. 6 Comparison of energy efficiency](image)

Fig. 6 Comparison of energy efficiency

Note that in Figs. 5 and 6, the curves for the Immediate-Send have one inflexion because of the maximum number of STAs that can be served in one BI while the curves for LAPS have one more inflexion because of the usage of PFDL under heavy load condition. In addition, the curves are straight lines like because this paper focuses on the impact of PS-Polls and data packets’ transmission order on the overall power saving performance and so ignores the additional waiting time brought by random access, as explained in section II.

V. CONCLUSION

This paper presented LAPS mechanism which uses the Immediate-Send mechanism under light load condition and a proposed PFDL mechanism belonging to the Later-Send method under heavy load condition. The Immediate-Send mechanism is demonstrated through analysis to have best power saving performance of both total power consumption and energy efficiency when all STAs can be served in this BI. Under heavy load condition, PFDL divides the BI into polling phase and data phase. After the polling phase, the AP transmits data successively to STAs having sent PS-Polls while the STAs not having sent PS-Polls are allowed to transit to doze state and thus avoid wasting power on continuous tries of sending PS-Polls throughout the whole BI. Therefore, the overall power consumption and average power consumed for one unit of payload are reduced. Numerical results show that LAPS outperforms the conventional Immediate-Send mechanism under heavy load condition, and the benefits increase with the data packet size which is related to PFDL’s overhead of the polling phase.

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