Performance Study of IEEE 802.11s PSM in FTP-TCP

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Abstract—**With the introduction of IEEE 802.11 power save mode (PSM), a lot of work has been done to enhance the energy saving ability of the nodes. The ultimate goal of the research is to make the networking equipments carbon neutral and prolong the lifetime of the energy limited devices for various applications; in some cases it is a trade-off between energy efficiency and delay. However, few studies have been made until now in the area of IEEE 802.11s based link specific power save mode. The link specific power save mode is a totally new concept. The essence of this method is the ability of a node to maintain different power save modes with its peer nodes. In this paper, the performance of the link specific PSM for FTP-TCP traffic is studied from the energy efficiency point of view. The throughput, the percentage of energy saving and the flow level fairness are examined in this study. Our results indicate that for a suitable combination of link specific PSM, the network not only achieves the same throughput as the active mode operation offers but also saves a significant amount of energy. The study also suggests that there is a trade-off among throughput, percentage of energy saving and fairness.**

Keywords-Link Specific Power Save Mode; IEEE 802.11; IEEE 802.11s; Peer Service Period; Deep Sleep; Light Sleep; TCP

I. INTRODUCTION

From the last decade, the deployment of mobile wireless devices has been rising by leaps and bounds in varieties of applications; such as in data access purpose, in wireless automation and control, making Voice over Internet Protocol (VoIP) calls as well as in other QoS sensitive applications. However, these mobile devices are battery powered and have limited amount of operational time. As the energy contained in the batteries is limited, devising an efficient energy saving protocol has become a critical issue for battery-constrained wireless devices. In basic PSM operation, the destined packets are temporarily buffered by the transmitter station (STA) and are later delivered to the destination STA in burst at some agreed-upon intervals. When the queue of the transmitter STA becomes empty, both transmitter and receiver can switch to doze state. A doze or sleep state is a low power state of the radio and consumes the lowest amount of energy.

With the introduction of IEEE 802.11 PSM operation, a lot of works have been done to reduce the energy consumption of the nodes while maintaining the QoS for various applications. Costa-Perez et al. [1] evaluated the performance of IEEE 802.11e at PSM via simulation. An algorithm is proposed by Namboodiri et al. [2] for VoIP traffic. The PSM operation in infrastructure mode is modeled by Yi-hua et al. [3]. Krashinsky et al. [4] proposed an algorithm for web traffic that bounds the delay to a user specified value. Hao Zhu et al. [5] proposed a rate based scheduling algorithm for streaming traffic. Gan et al. [6] proposed a power conservation scheme to optimally schedule the awake time of STAs to reduce the contention. Lei and Nilsson [7] modeled the queue for the infrastructure mode. Baek et al. [8] later extended this work and derived the exact average doze state and variance of delay. Chao et al. [9] proposed a quorum based energy conserving protocol for a single hop mobile ad hoc network (MANET). Lee et al. [10] used the Kalman filter to predict the best Ad hoc Traffic Indication Message (ATIM) window size.

Although a lot of works have been done in IEEE 802.11 based PSM, few papers are found to focus on the IEEE 802.11s based link specific PSM operation. In this scheme, a mesh STA creates link with peer mesh STAs and maintains a link specific power mode towards each peer. It only exchanges data frames with its peer STAs. The link specific power modes are active, light sleep and deep sleep. The power modes of peerings are independent and a mesh STA may operate in different power modes for each peering [11]. While in PSM, a mesh STA alternates between two states, awake and doze state. A Peer Service Period (PSP), an agreed contiguous time period, is used to exchange buffered frames in a link if the receiver STA is in PSM, i.e., it operates in light sleep or in deep sleep mode for the link. The IEEE 802.11s has proposed its own guideline to initiate, maintain and terminate a PSP.

Energy saving in a PSM STA is achieved by switching off the radio when the system is busy to serve other STA. However, a STA that has already initiated a PSP to retrieve its buffered packets listens to the channel and waits for its turn when other STA is served by the system. Thus, in a large system, the total listening time of a particular STA is significant and could be much larger than the total receiving time of its own packets. In case of bidirectional traffic, suppose for TCP, this listening time could be further increased for TCP acks or due to the contention between TCP payload and TCP ack. This additional listening time, apart from the actual receiving time of the packet, costs extra energy and

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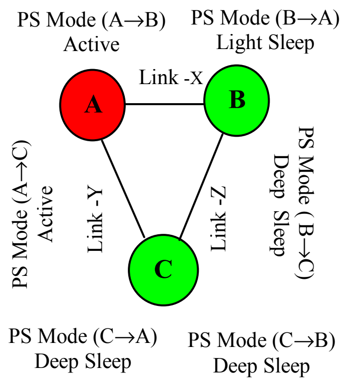

Figure 1. Link specific power modes of three mesh STAs. STA A is in active mode. STA B and C are in PSM.

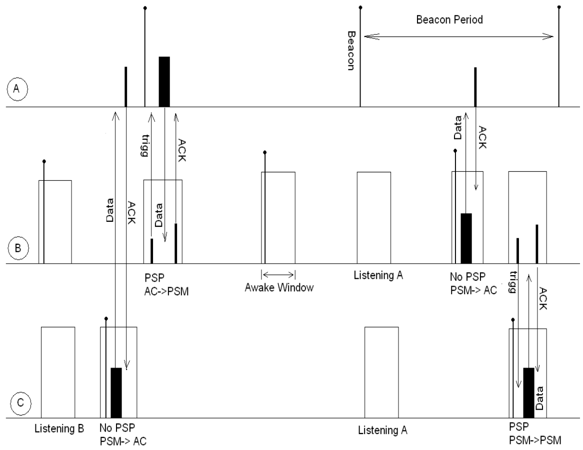

Figure 2. The internal states of mesh STAs during frame transmission and reception. A is in active mode. B and C are in PS mode. STA's PSM to links are given in Figure 1.

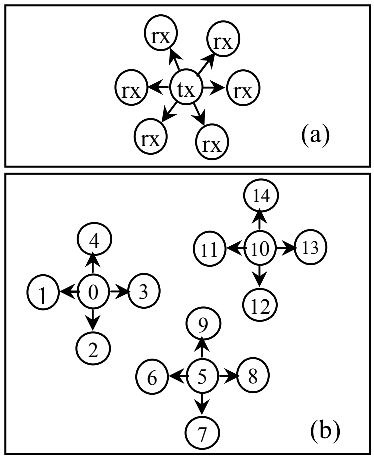

Figure 3. (a) First scenario. Single cluster. tx=TCP sender, rx= receiver. (b) Second scenario of 3 clusters. STA indexes are at the center.

degrades the PSM performance. The similar thing happens in case of packet transmission. If several PSPs continue at the same time, a particular transmitting STA has to listen to the channel while other STA transmits. This obviously prolongs the awake state of a PSM STA.

In this paper, the performance of the IEEE 802.11s PSM for FTP-TCP traffic is investigated from the energy efficiency point of view. It is found that by selecting the suitable beacon period and PSM link combination, significant amount of energy could be preserved while offering the same throughput as the active mode operation offers.

The rest of the paper is organized as follows: the PSM link concept and the frame exchange methods in the IEEE 802.11s are discussed in Section 2. The TCP and flow throughput is addressed in Section 3. The simulation results are discussed in Section 4. The conclusion is drawn in Section 5.

II. IEEE 802.11s System

In this section, the IEEE 802.11s PSM link concept as well as the frame transmission and reception method in a link in PSM is introduced.

A. The PSM Link Concept in IEEE 802.11s

A link connects two mesh STAs and both STAs can operate in any of the three power modes for the link independently. These modes are active (AC), light sleep (LS) and deep sleep (DS). A mesh STA can serve its various peers in different power modes at the same time. In Fig. 1, STA A is in active mode for both link-X and link-Y. STA C is in deep sleep for both link-Y and link-Z. The same STA B is in light sleep for link-X and in deep sleep for link-Z.

In the 802.11s, the beacon transmission times are evenly distributed in the beacon interval as shown in Fig. 2. In light sleep mode for a link, a PSM STA wakes up periodically to listen to all the beacons of the peer STA of the link. In deep sleep mode for a link, a PSM STA may not wake up to listen to all the beacons. In active mode operation, a STA remains in awake state all the time. In LS or DS mode, a STA alternates between awake and doze states, as determined by the frame transmission and reception rules [11].

B. Frame Transmission and Reception Method

In PSM operation, as shown in Fig. 2, a mesh STA first enters the awake state prior to its every Targeted Beacon Transmission Time (TBTT) and remains in this state for awake-window duration after the transmission of beacon. A mesh STA announces the presence of buffered data in the beacon's traffic-indication-map (TIM) element.

The awake state could be extended if any PSP is initiated with peer STA within the awake-window duration. In this case, the STA will remain in awake state until the PSP is terminated successfully. If no PSP is initiated, the mesh STA should return to doze state just after the awake-window. A PSP is a contiguous period of time during which the buffered frames are transmitted to the PSM mesh STAs. After hearing the presence of data, a peer STA triggers the beaconing STA to initiate a PSP as shown in Fig. 2. A trigger might be a mesh data or mesh null packet which should be acknowledged. After receiving the trigger, the beaconing STA starts to transmit the buffered packet one by one. The PSP will be terminated after a successfully acknowledged data frame or a mesh null frame with the End of Service Period (EOSP) bit set to 1 from the transmitter of the PSP [11]. However, a PSM STA can transmit frames to its AC mode peer STA at any time without establishing a PSP, but the frame transmission towards a PSM peer will never take place arbitrarily. As shown in Fig. 2, PSP should be established before a transmission takes place towards the PSM peer.

III. TCP TRAFFIC AND FLOW THROUGHPUT

TCP is a window-based transport layer protocol. The congestion window is dynamically adjusted in response to a successfully received acknowledgement (*ack*) packet. The window size is measured by the number of maximum segments (MSS) that can be transmitted within a transmission timeout interval without any acknowledgement. The timeout interval is calculated from the estimated round trip time (RTT) of a packet. When a TCP connection starts, the congestion window is initialized to 1. A threshold value is also initialized in this stage. Until there is a loss event, the TCP sender redoubles its congestion window at every RTT. From the sender side, loss event could be the occurrence of either time out or the reception of multiple duplicate *ack* [12]. However, in this primary phase, the congestion window grows exponentially up to the threshold value for every successfully received *ack*. This starting property is called slow starting (SS). When the threshold value is reached, the congestion window is increased by one MSS at every RTT until any loss event occurs. During this whole process if any loss event occurs, the threshold value is reset to one half of the previous value and the congestion window is reinitialized to one.

The RTT has a significant impact on TCP throughput. The average throughput decreases as the RTT increases. The small RTT means high rate of arrival of positive acknowledgement. As a result, the smaller the RTT is, the faster the congestion window develops. The large congestion window creates high bursts of packets and increases the throughput of a flow. The average throughput [12] of a connection at steady state could be expressed as follows:

$$Average\ Throughput = \frac{0.75 \times W}{RTT} \quad (1)$$

Here W is the value of the congestion window when a loss event occurs. It is assumed that W and RTT are approximately constant over the duration of the connection.

IV. PERFORMANCE EVALUATION

The IEEE 802.11s PSM related operations such as beacon management, PSP protocol, PSM efficient queue as well as peer specific buffers on top of the queue are implemented by the authors in the Network Simulator NS-2.33. TCP Tahoe is used in the simulation. In order to evaluate FTP-TCP performance, two types of scenarios are considered. In the first scenario, users download from a common server in a star topology as illustrated in Fig. 3 (a). In this case, the number of active users is increased gradually from one to twelve. In the second scenario, as shown in Fig. 3(b), three clusters, each consisting of four users, are deployed and the clusters are interfering with each other. The numbers of flows are also kept constant during the simulation. Throughout this paper, the PSM link combination is expressed by writing their corresponding power save mode beside an arrow sign. Suppose LS<->DS means the server or the transmitter STA is working in LS mode for the link and the users or receiver STAs are working in DS mode for the link.

TABLE I. Simulation Parameters.

Parameters	Values
TX state power	1.327W
RX State power	0.967 W
Idle state (neither TX nor RX state) power	0.844 W
Doze state power	0.066 W
Energy per Switching	0.422mJ
Switching time, from doze to idle state	250µs
Beacon transmission interval*	102.4ms
Data transmission Rate	6Mbps
TCP (Tahoe) segment size	1000Byte
Beacon frame size	272Byte
PSP Trigger frame size	28Byte
Awake Window duration	5ms
Safety margin or wakeup before TBTT	0.1024ms
DIFS	34µs
SIFS	16µs
CW Slot duration	9µs
CW_{min}	15

* Unless otherwise stated

In this experiment for LS<->LS mode, the receiver obtains its TCP payload when it wakes up to listen to the server's beacon and the server gets the buffered TCP acks when it wakes up to listen to the receiver's beacon. The TCP acks and payloads are thus transferred in separate PSP. However, in LS<->DS mode, the receiver hardly wakes up to listen to the server's beacon as it operates in DS mode for the link. Therefore, when server wakes up to listen to the receiver's beacon, a bidirectional PSP is established to transfer buffered TCP acks and the buffered TCP payload. In AC<->DS mode of operation, the receiver retrieves its TCP payload when it wakes up in its own TBTT. It triggers the server and establishes a PSP. However, the receiver can send the TCP acks any time as the server operates in active mode all the time. When the receiver's queue gets the TCP acks from the upper layer, it immediately transmits the packet to the active mode peer without any PSP. In order to do this, it switches to awake state if necessary.

The throughput, percentage of energy saving and flow level fairness are examined in this study. The percentage of saving is the percentage of saved energy to successfully transmit a single bit in PSM when compared to Active mode (AC<->AC) operation.

$$Saving = \frac{Energy/\,bit\ in\ AC - Energy/\,bit\ in\,PSM}{Energy/\,bit\ in\,AC} \times 100 \quad (2)$$

Here Energy/bit is the energy expended to transmit one bit successfully. The energy model [13] and other simulation parameters are given in Table I. The free space channel model is used throughout the simulation in order to focus on the MAC performance in this energy related issue. Hence, packets are lost only when collision occurs.

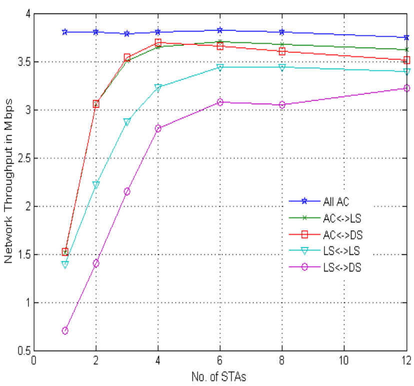

Figure 4. Network throughput for different PSM link combination. The numbers of receiving STAs are increased gradually. Transmission rate is 6Mbps.

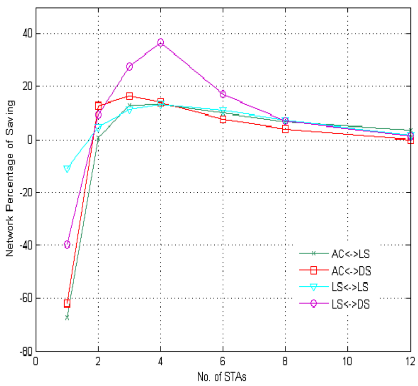

Figure 5. Network percentage of saving for different PSM link combination. The numbers of receiving STAs are increased gradually.

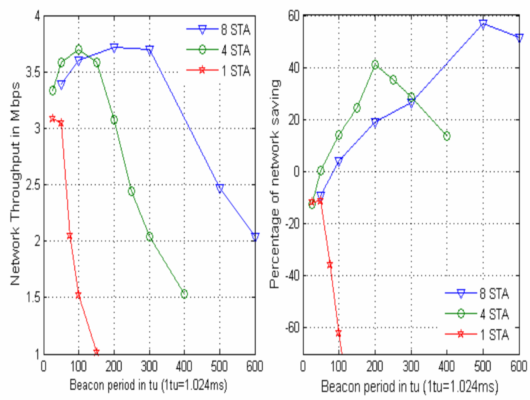

Figure 6. Throughput and saving in AC<->DS mode as Beacon period varies. Users are downloading simultaneously. 1, 4 and 8 users are taken into consideration.

A. Results For First Scenario

In the first scenario as shown in Fig. 3(a), users download simultaneously from a common server (STA0) in a star topology. The performances are first measured by keeping the beacon period constant (100 tu) as shown in Fig. 4 and 5. Later, the impact of beacon period is studied in Fig. 6 by varying the beacon transmission interval. Here one time unit (tu) is equal to 1.024 ms.

Fig. 4 shows the network throughput for different PSM link combination. Network throughput means the summation of individual throughputs of all links in a network. In PSM operation, as the receiver STAs periodically wakes up to receive the buffered data, the TCP sender experiences a large RTT for the flow. As discussed in Section 3, this large RTT in turns reduces the average throughput. For the small number of PSM clients, the channel capacity remains under utilized, irrespective of the PSM link combination. However, when the channel utilization rises for multiple downloading users, the difference of network throughputs between PSM and AC mode becomes marginal. The Fig. 4 also shows that when the server works in PSM for its PSM peer, the utilization of channel is lower than that when it works in AC mode for its PSM peer. Actually if the server operates in AC mode, the PSM STA can send the TCP ack immediately to the server without establishing any PSP. This decreases the RTT and thus increases the throughput. The fairness among the flows, when all users are downloading, is observed in scenario 2 in the subsequent section where interference is comparatively high.

Fig. 5 shows that the percentage of energy saving in a network varies with the number of downloading users. The percentage of saving is calculated for the whole network. In PSM operation, a fixed amount of energy is required to maintain the link regardless of data. Link maintenance requires periodic wakeup for listening peers, transmitting beacon, switching and alternating between doze and awake state. These activities consume a certain amount of energy. For a single user, the channel capacity is highly under utilized and thus the cost per bit in PSM is higher than that in AC mode operation. In AC<->DS mode, the saving is around 16.30% for 3 users, 4% for 8 users and tends to 0% for 12 users. As discussed in Section 1, the additional listening time in a dense network increases the overall energy consumption.

Though the percentage of saving is higher in LS<-DS mode, this PSM link combination offers around 25% less throughput when compared with AC<->DS mode as given in Fig. 4. Lower throughput also means more delay to download a file.

The impact of beacon period on throughput and saving is explored in Fig. 6 for AC<->DS mode. In the 802.11s, beacons are evenly distributed in a beacon interval. At small beacon period, the distance among the wakeup-instant of the STAs is also small. Therefore, before the completion of an ongoing PSP, another STA wakes up and establishes its own PSP. This introduces contention among STAs in the network. For a large beacon period a STA can get sufficient time to complete its PSP before another STA wakes up. Hence, up to a certain point, the throughput increases with the increase of beacon period. A large beacon period on the other hand introduces large sleep time or large RTT for a TCP sender. As a result, throughput starts to fall at some point when impact of RTT becomes prominent. The Fig. 6 also shows that there is a trade-off between throughput and percentage of saving and the optimum beacon period depends on the number of users in a cluster.

B. Results For Second Scenario

In the second scenario as shown in Fig. 3 (b), three clusters of each consisting of four active users are deployed. STA 0, STA 5 and STA 10 are TCP senders. In PSM, the links are configured as AC<->DS, i.e., TCP senders are working in AC mode for their links. Fig. 7 illustrates the individual link throughput and the percentage of saving of each node at beacon period 100 tu. The red bar and green bar in 7(a) shows the throughput/link in AC mode and PSM respectively. There is a marginal difference between the throughputs of the two modes. Besides this, the network throughput is 2.538 Mbps

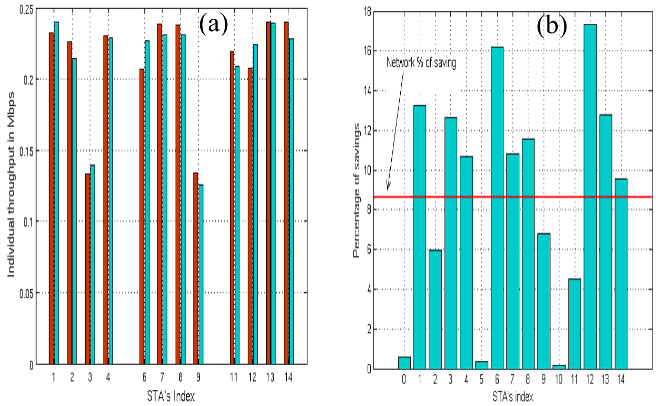

Figure 7. (a) Red and green bars show the throughput/STA in AC and PSM respectively. There is marginal difference between AC and PSM throughput. (b) Depicts the percentage of saving of individual STAs.

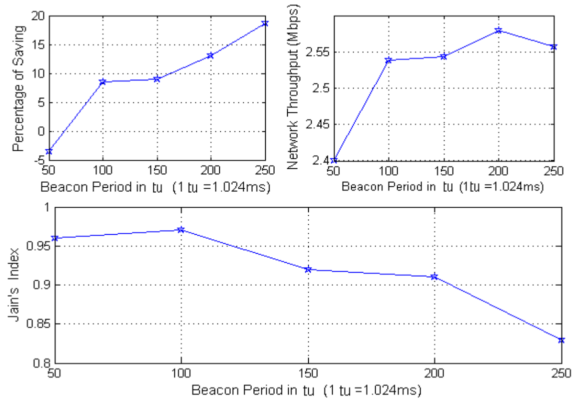

Figure 8. Beacon period vs. throughput, energy-savings and Jain's indexes are plotted. There is a trade-off among them .

and 2.546 Mbps in PSM and AC mode respectively, i.e., both modes offer almost equal throughput. Fig. 7(b) depicts the percentage of saving of individual STAs. The energy saving of the whole network is indicated by the horizontal red line in the figure and it is around 8.54%. Fig. 8 depicts the impact of beacon period on throughput, energy saving and fairness among flows in terms of Jain's index. As explained in previous section, the percentage of saving, throughput and fairness varies with the beacon period.

V. CONCLUSION

In this paper, a performance study is performed for the case where a number of users are downloading a file from a specified server using TCP connection. The study demonstrates that if the server operates in PSM for the link, it may introduce more delay when compared with its AC mode operation. Due to high throughput or small delay, AC<->DS link combination could be a good choice for such operation. PSM operation not only offers the same throughput and fairness as active mode offers, but also saves a significant amount of energy. The percentage of saving depends on the network size and topology.

The study indicates that there is a trade-off among throughput, percentage of saving and fairness. The beacon period has a significant impact on energy saving, throughput and fairness. The optimum beacon transmission interval depends on the number of users and the topology of the network. For example, when the percentage of saving is the primary concern, the beacon transmission interval of 200 tu can maximize the percentage of saving to 40% for an isolated cluster of 4 STAs. In future, this study could be further extended by deploying some PSM STAs together with some active mode STAs in the same network. The effect of the channel as well as the impact of service order of flows on PSM efficiency could also be examined in detail.

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