for MAC Protocol in Ad Hoc Networks

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***Abstract*— Ad hoc networks have recently become a hot topic. In ad hoc networks, battery power is an important resource, since most terminals are battery powered. Terminals consume extra energy when their network interfaces are in the idle state or when they overhear packets not destined for them. They should, therefore, switch off their radio when they do not have to send or receive packets. IEEE802.11 features a power saving mechanism (PSM) in Distributed Coordination Function(DCF). In PSM for DCF, nodes must stay awake for a fixed time, called ATIM window (Ad-Hoc Traffic Indication Map window). If nodes do not have data to send or receive, they enter the doze state except for during ATIM window. However, ad hoc networks with PSM have larger end-to-end delays to deliver packets and suffer lower throughput than the standard IEEE802.11. To solve this problem, this paper proposes a protocol that reduces delay and achieves high throughput and energy efficiency. Simulation results show that our proposal outperforms other PSMs in terms of throughput, end-to-end delay and energy efficiency.**

I. Introduction

Recently battery powered devices, such as Handheld PC, have made the mobile computing a reality. Wireless ad hoc networks can provide data communication among these devices irrespective of their physical locations. However, many constraints are imposed on them by the environment. Furthermore, since ad hoc networks typically consist of energy constraint nodes and their power is provided by batteries, nodes need to conserve their energy to maximize battery life. Power conservation is one of the most important issues.

Several experimental results, [1],[2],[8], show that energy in ad hoc networks is not always consumed by actual communication. This means wireless network interfaces in the idle state waste a significant amount of energy. Energy dissipation in the idle state cannot be ignored because network interfaces often stay in the idle state for a long time. Thus to conserve this energy, it is generally desirable to turn the radio off when they are not in use. This observation has led to several energy conservation protocols, [8], [9] being proposed to reduce energy consumption in dense ad hoc networks by turning off devices that are not necessary for global connectivity. However, in these protocols, geographical or topological information decides which set of nodes have their radios turned on, thus those nodes still consume their energy supply even when there is no actual traffic load on the networks [5].

Some MAC protocols have also been proposed to conserve energy [5],[6], which were based on IEEE 802.11 PSM. The general idea of PSM is for all nodes with it to keep their radios off when they do not have to send or receive packets, and they turn on their radios at the same time, maintaining the awake state for a specified period. For that period, a sender announces buffered packets to a receiver via an ATIM frame. A node that receives such an announcement frame recognizes that the sender wants to transmit packets to it, and stays awake until the packet is delivered. Of course the nodes must be synchronized to awaken at the same time. The IEEE802.11 standard [3] contains two medium access control protocols, PCF (Point Coordination Function) for a centralized protocol and DCF (Distributed Coordination Function) for a distributed protocol. Both protocols support PSM. Nodes in PSM must be synchronized by periodic beacon transmissions. In this paper we focus on PSM in DCF.

MAC protocols have the ability to sense medium and decide when packets can be transmitted or received. They are thus suitable for playing a role in turning off the radio when it does not have to be used. Thus, our proposal uses MAC layer information to switch off wireless network interfaces. As with [5] and [6], it is also based on IEEE 802.11 PSM. It can improve the performance of throughput and end-to-end delay, comparing with other PSMs.

The remainder of this paper is organized as follows. The next section reviews PSM in DCF. Section 3 shows related works. Section 4 presents our proposed protocol. In section 5, we describe our simulation model and discuss simulation results. Finally, section 6 concludes the paper.

II. IEEE802.11 PSM in DCF

In this section, we present PSM in DCF, for which Fig.1 shows the details. Fig.1 shows that time is divided into beacon intervals, and at the beginning of each beacon interval, there exists a specific interval, called ATIM window. During an ATIM window, every node is awake, and for nodes to wake up at the same time, they need to be synchronized by beacon

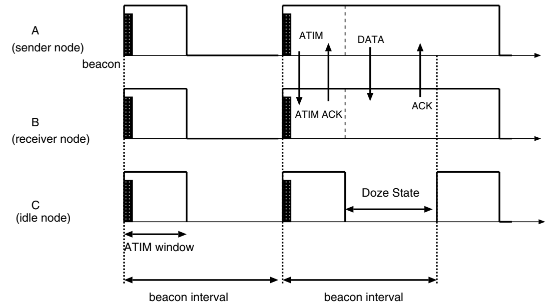

Fig. 1. Power Saving Mechanism for DCF

transmissions. Because of the absence of a centralized timer in ad hoc networks, each node is responsible for generating a beacon. After the beacon interval, all nodes compete for transmission of the beacon using a standard backoff algorithm. The first station wins the competition and all others have to cancel their beacon transmissions and adjust their local timers to the time stamp of the winning beacon. Packets for a node in the doze state have to be buffered by the sender until the end of the beacon interval. When a node, like node A in Fig.1, has a pending packet to transmit, it transmits an ATIM frame to a receiver node, like node B in Fig.1, during an ATIM window. When the receiver node receives the ATIM frame, it replies with an ATIM-ACK. After the ATIM and ATIM-ACK handshakes, both the sender and receiver stay awake for the remaining beacon interval to perform data transmission. A node that has not performed the ATIM and ATIM-ACK handshakes during the ATIM window falls back into the doze state after the ATIM window.

The performance of PSM is affected by the size of the ATIM window. It was shown in [4] that PSM performed well when the length of the ATIM window was approximately 25% of the beacon interval. Furthermore, during an ATIM window, DATA frames cannot be transmitted. Overheads in energy consumption occur when transmitting or receiving additional ATIM and ATIM-ACK frames. There is a time overhead in time due to an ATIM window, since data can be transmitted after the ATIM window. From these perspectives, PSM using DATA window was proposed in [6], and was called *new PSM* (NPSM). NPSM exhibited better performance with respect to aggregate throughput and energy conservation. The next section explains NPSM in detail.

PSM still suffers some problems with end-to-end delay and throughput, since in ad hoc networks source nodes use multi-hop wireless communications to deliver packets to destination nodes. If a sender in PSM wants to transmit packets to a receiver, it has to inform the receiver of its pending packets by an ATIM frame before sending them. In other words, if a sender wants to immediately transmit them to a receiver and has not transmitted an ATIM frame to the receiver, it cannot send packets at once. Therefore, PSM shall make larger delay than normal IEEE 802.11, and the delay in PSM shall be accumulated through multi-hop wireless connections. Furthermore, if a network has large traffic load, then a sender in PSM cannot inform a receiver of its pending packets by ATIM frames for an ATIM window, so throughput declines. Therefore, ad hoc networks in PSM have large end-to-end delay and degrade throughput. In this paper, we improve PSM against delay and throughput and propose IPSM (Improved PSM).

III. Related Works

A. On-demand Power Management

This subsection presents a MAC protocol that uses on-demand power management [5]. It is a cross-layer protocol designed by network layer information and cooperates with on-demand routing protocols. Nodes usually operate in PSM. If nodes receive routing control packets or data packets, they switch from PSM to the active mode (AM). In AM, a node is in the awake state and transmits or receives data at any time. Transitions from AM to PSM are determined by a soft-state timer, and timer values depend on the type of packets received. When the timer expires, a node reverts from AM to PSM. The soft-state timer is refreshed by communication events that trigger a transition to the active mode.

When nodes in PSM have packets to send, they have to transmit the ATIM frame to receiver nodes during an ATIM window. However, if neighbor nodes of a sender node that has to send ATIM frame to a receiver node are in AM, data packets transmitted by them may disturb the ATIM frame exchanges. Furthermore, this protocol can cooperate only with on-demand routing protocols, and if new on-demand routing protocols are developed, the PSM proposed in [5] will not be able to adapt to them. Therefore, we believe that it is desirable for PSM to be developed separately from network layer.

B. New PSM (NPSM)

This subsection describes the NPSM proposed in [6]. NPSM does not use ATIM and ATIM-ACK frames, since they waste bandwidth and consume energy. Fig.2 illustrates NPSM in DCF. In Fig.2, nodes A and B are a sender and a receiver, respectively. Node C does not send any packets, but can overhear packets traveling from node A to node B.

Time is divided into beacon intervals in NPSM as well as in PSM. At the beginning of each beacon interval, every node in NPSM enters the awake state for a specific duration, called a DATA window; all nodes in NPSM stay awake during the DATA window. They do not send ATIM and ATIM-ACK frames, but can transmit data packets during a DATA window. The ATIM window in PSM plays a role in announcing pending packets to receiver nodes, though NPSM has a different way to achieve the same function. In NPSM, each node X has the following counters to indicate the number of packets to transmit or receive.:

- $T(i)$: the number of packets pending at node X for node i.
- $R(i)$: the number of packets destined for node X. Node X knows they are pending at node i.
- $R_{total}(X)$: sum of $R(i)$ over all neighbors of node X.
- $U_p(i)$: the number of packets that the neighbor node i needs to transmit and receive.

DATA, RTS, CTS, and ACK packets have some of these counters. When node i transmits a DATA packet to node j, it

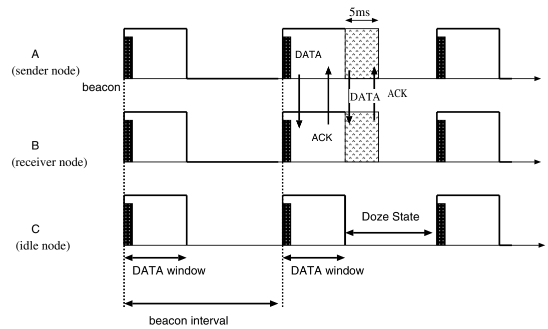

Fig. 2. NPSM for DCF

includes $T(j)$ and $R_{total}(i)$. When node j receives the DATA packet from node i, it updates $R(i)$. A RTS from node i to node j includes $T(j) + R_{total}(i)$. Furthermore, a CTS and ACK from node j to i includes $T(i) + R_{total}(j)$. When each node receives or overhears a RTS, CTS, DATA or ACK packet exchanged between node i and node j, it updates $U_p(i)$. Here, $U_p(i)$ shows data transmissions that the node i will receive or send while staying awake. Therefore if node k has $U_p(i)$ greater than zero, it can recognize node i stays awake. $U_p(i)$ is reset to zero at the beginning of each beacon interval. In NPSM, every node stays awake during a DATA window. When a DATA window expires, nodes extend the DATA window or go into the doze state. When the following conditions are satisfied, they extend the DATA window. If $R_{total}(k)$ at any nodes k is greater than zero, they extend the DATA window to receive packets. As shown in Fig.2, sender node A has packets to transmit to receiver node B on the expiration of the DATA window. In this condition, node A infers the state of node B by means of $U_p(B)$. If $U_p(B)$ is not maintained by node A or $U_p(B)$ is zero, node A cannot transmit packets to node B. It will transmit them in the next beacon interval and go to the doze state except when $R_{total}(A)$ is greater than zero. In [6], DATA window size is increased in increments of 5ms. When the extended DATA window expires, the same process is repeated as when the initial DATA window expires.

Since NPSM removes the ATIM window, it conserves energy for ATIM frame handshakes; bandwidth for data transmission is used more effectively. However, a sender node in NPSM informs a receiver node of its pending packets as well as in PSM ,so that end-to-end delay is still large through multi-hop connections. The reason for this phenomenon was shown in the previous section. Furthermore, when network traffic load is high, a sender node cannot transmit packets to a receiver node during a DATA window due to traffic congestion. Since the sender infers the state of the receiver i by $U_p(i)$ that is reset to zero at the beginning of each beacon interval, it cannot know the receiver's state if it does not successfully transmit packets during each initial DATA window. Consequently, throughput deteriorates in NPSM. This condition similarly happens in PSM. Therefore, in the next section, we present our proposed IPSM to improve throughput, delay, and energy efficiency. It can work only with information from the MAC layer.

IV. Improved Power Saving Mechanism (IPSM)

A. Overview of IPSM

The goal of IPSM is to achieve performance almost the same as in normal IEEE 802.11 with respect to end-to-end delay and throughput, and furthermore, not to degrade the performance of energy conservation. Before we express our proposed algorithm of IPSM, we summarize conditions required for each performance measure, energy consumption, throughput, and end-to-end delay.

- **energy consumption:** To reduce energy consumption, nodes must remain in the doze state for as long as possible.
- **throughput:** To adapt to a high network traffic load, nodes in routes have to be awake during data transmissions.
- **end-to-end delay:** For PSM to achieve the same performance as normal IEEE 802.11, nodes in routes have to stay in the awake state. It generates large delays for a sender to inform a receiver of its pending packets in PSM and NPSM.

Considering the above requirements, we find that the relation among energy consumption, throughput and delay is a trade-off, and that the performance of each factor depends on traffic patterns. Therefore we need to balance the trade-off and consider traffic to decide when a node goes into the doze state. However, since it is very difficult to predict packet arrivals and all network conditions, we cannot completely optimize the awake period.

The key idea of our proposed IPSM is that nodes in routes stay awake and others continue to doze. Furthermore, regarding energy efficiency and bandwidth utilization, IPSM uses a DATA window instead of an ATIM window. However, nodes in IPSM do not maintain counters of pending packets, since announcing buffered packets results in large delays. Instead, each node in IPSM possesses a neighbor table that holds neighbor node ids and the awake period of neighbor nodes. Consequently, when a node receives packets, it can immediately relay them if it knows from its neighbor table that the next hop is awake. To balance the trade-off between throughput, delay and energy consumption, the awake period can be varied in IPSM. In the following subsections, we show how to decide the awake period and how to announce the awake period of each node to neighbor nodes.

B. Awake Period

Fig.3 and 4 illustrate how nodes in IPSM change their state. Fig.3(a) shows that if node A receives a data packet including broadcast packet, it stays awake for the rest of the current and the next beacon interval to wait for packet arrivals. If node B receives a data packet, as shown in Fig. 3(b), it also continues to stay awake for the rest of the current and the next beacon interval. Moreover, when a node is awake and receives a data packet after a DATA window, it stays awake during the rest of the current and the next beacon interval. Fig.4 presents how node A reduces its awake period. In Fig. 4, node A does not receive any data packets during a beacon interval, thus it reduces its awake period in the following beacon interval to

$\frac{T}{2}$, which includes a DATA window. Here, T denotes beacon interval and T_D represents a DATA window. If node A does not receive any data packets during $\frac{T}{2}$, its awake period, $\frac{T}{2}$, is further reduced by half, i.e.,$\frac{T}{4}$. As far as energy consumption is concerned, a shorter awake period results in more efficient energy conservation. However, receiver nodes need to remain in the awake state and wait for packet arrivals for a while, since the interval of packet arrivals fluctuates and the trade-off previously mentioned should be balanced. Therefore, if data packets do not arrive, the awake period is set to half of the previous awake period. If an awake period is under DATA window, it will be set to DATA window, T_D.

C. Announcing Awake Period

Since every node is awake during a DATA window, sender nodes can transmit packets to receiver nodes during that period. However, to transmit packets after a DATA window, a sender node has to know whether a receiver node is awake. IPSM enable nodes to inform neighbor nodes of their awake period in the following way: Each frame, RTS, CTS, DATA, and ACK, contains the length of each transmitter node's awake period. The minimum length of the awake period is a DATA window, T_D. Each node has a neighbor table that contains neighbor node id and the length of its awake period. If a node receives or overhears each frame, it will update the length of the awake period in a corresponding entry. Each entry in a neighbor table is updated at the beginning of each beacon interval; that is, the length of the awake period in each entry is reduced by half. When a sender node wants to transmit packets and does not hold the entry of a receiver node, it decides that the length of the awake period of the receiver node is the DATA window. In this case, it recognizes the receiver is in the doze state after the DATA window and will transmit the packet in the following beacon interval.

Sender nodes in NPSM have to announce buffered packets to receiver nodes. When sender nodes in NPSM have no buffered packets, they enter the doze state except for when their counters for receiving packets are greater than zero. In other words, they have to buffer packets to stay awake. Wireless multi-hop networks with NPSM have large delays due to buffering at intermediate nodes. Nodes in NPSM increase their awake period in increments of 5 ms when they have packets to transmit or receive, and in particular, sender nodes decide to extend their DATA window by pending packets and the $U_p(i)$ of receiver node i. $U_p(i)$ is reset to zero at the beginning of each beacon interval. When traffic congestion occurs and sender nodes cannot receive any packets from receiver nodes, they will not know the counter value of receiver node i, thus they will not be able to transmit packets after the DATA window. On the other hand, since nodes in IPSM inform their neighbors of only their awake period, sender nodes do not have to buffer packets to remain in the awake state. In IPSM, intermediate nodes can relay packets immediately after receiving them. Consequently, networks in IPSM have shorter delay than other PSMs. Furthermore, since each node stays awake during the rest of the current and the next beacon interval when it receives only one packet, nodes in IPSM do not have to try to send or receive packets to stay awake in every beacon interval. As a result, IPSM can adapt to high traffic load and achieve higher throughput than other PSMs.

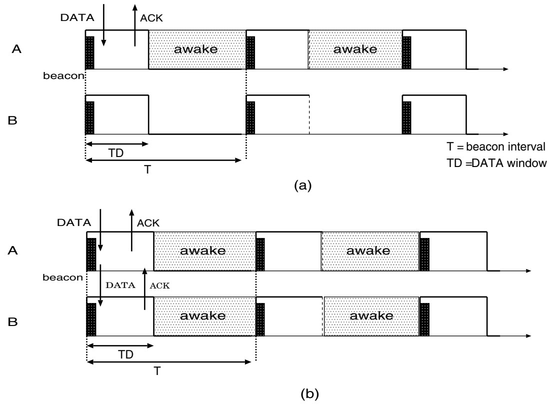

Fig. 3. Transition to awake state

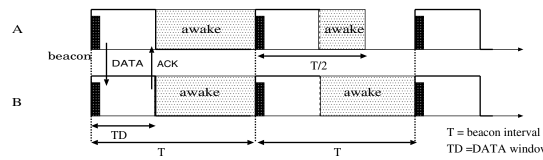

Fig. 4. Transition to awake or doze state

V. Performance Evaluation

We implemented IPSM using NS-2 [7], and performed several simulations using different patterns of traffic, long-lived CBR traffic and on-off traffic. We consider four different types of MAC protocols: normal IEEE802.11, PSM, NPSM, and IPSM. For each simulation, every node is equipped with IEEE 802.11 based WaveLAN wireless radios with a bandwidth of 2 Mbps and transmission range of 250 m. DSR is used as the routing protocol. The simulation area is 1500 m $\times$ 500 m and contains 30 nodes. The energy model is the same model as in [8]. We assume that a radio consumes 1.4W for transmitting, 1.0W for receiving, 0.83W when listening but idle and 0.13W for sleeping. The length of data packets is 512 bytes. The beacon interval is 100 ms, and each ATIM and DATA window is set to 25 ms [4]. For NPSM, the incremental awake time is 5 ms as was used in [6]. The efficacy of power consumption can often be evaluated by how long networks remain operational. However, the lifetime of a network is closely related to how it is used. If a protocol can promote high throughput, the lifetime of the network on which it is implemented may be short. Therefore, we use *energy goodput* described by Eq.(1) to evaluate power efficiency [5]:

$$energy\ goodput = \frac{total\ bits\ transmitted}{total\ energy\ consumed} \qquad (1)$$

where the total bits transmitted are calculated for application layer data packets only. The unit of energy goodput is bits/J, which in essence captures the energy utilization of the network with all control overheads considered. We evaluate the efficiency of data delivery by the end-to-end delay and the packet delivery ratio, which is defined as the total number of packets received divided by the total number of packets transmitted. Other simulation conditions are presented in each simulation.

A. Simulations for long-lived CBR traffic

We performed simulations to study IPSM in a network with long-lived CBR connections at different transmission rates. Here, we evaluate the packet delivery ratio, end-to-end delay and energy goodput for different protocols. Source-destination pairs are randomly chosen during the simulation time, 300 s. Fig.5 shows packet delivery ratio as traffic load changes, clearly indicating that, compared with normal IEEE 802.11, the packet delivery ratio in IPSM declines, but IPSM has a higher packet delivery ratio than other power saving mechanisms. This is because nodes with IPSM do not have to announce information on pending packets and can stay awake to wait for arrivals of data packets, even if the network has a high traffic load. If a receiver node receives only one packet, it can remain in the awake state during the remainder of the current and the next beacon interval. However, in other power saving mechanisms, sender nodes have to announce information about buffered packets to receiver nodes during each ATIM or DATA window to stay in the awake state after that period. Therefore, if traffic congestion occurs, sender nodes cannot inform receiver nodes of pending packets to stay in the awake state after the ATIM or DATA window. For example, it is difficult for sender nodes with NPSM to know the counter values of receiver nodes during every DATA window when the traffic load is high. As a result, the packet delivery ratio declines. This condition often happens when networks have heavy traffic loads. Fig.6 shows a comparison of end-to-end delay in different power saving mechanisms. Since nodes with IPSM do not need to announce pending packets, they can relay packets immediately after they receive the packets. In other power saving mechanisms, announcing pending packets causes large delays in wireless multi-hop networks because sender nodes have to buffer packets before informing receiver nodes of them. For these reasons, IPSM gives shorter delays than other power saving mechanisms; consequently, there is little difference between IPSM and normal IEEE 802.11. As shown in Fig. 7, our proposed IPSM achieves the highest energy goodput at high traffic loads. It is clear that IPSM can realize energy efficient data delivery. At low traffic loads, NPSM shows better energy goodput than IPSM because nodes in IPSM stay awake to wait for packet arrivals longer than in NPSM. However, at higher traffic loads, sender nodes in NPSM cannot inform receivers of pending packets during a DATA window, and then they cannot continue to stay awake to transmit packets. Moreover, since nodes with NPSM or PSM have to announce buffered packets to stay awake and to transmit them, data packets received by intermediate nodes cannot be smoothly relayed.

Upon analyzing these simulation results, we see that IPSM can balance the trade-off between throughput, delay and energy consumption and exhibit performance superior other power saving mechanisms.

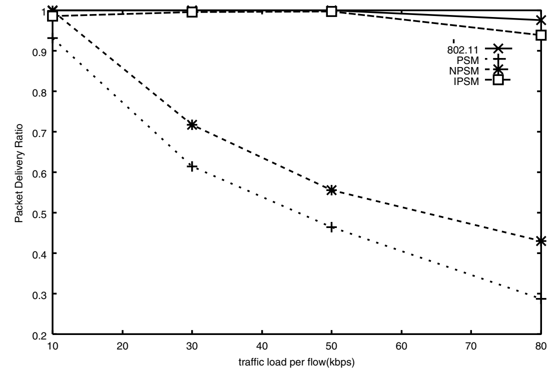

Fig. 5. Packet delivery ratio, 5 long-lived CBR connections

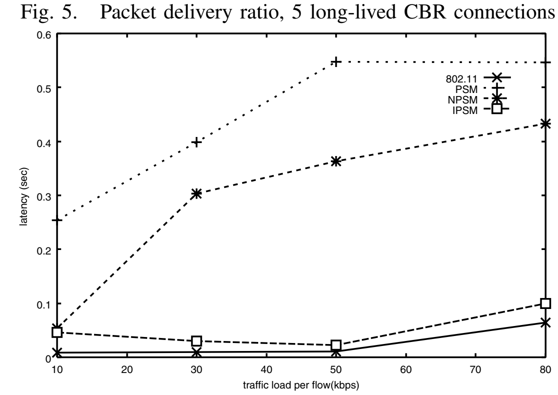

Fig. 6. Comparison of end-to-end delay, 5 long-lived CBR connections

B. Simulations for on-off traffic

To understand our proposed IPSM's performance under realistic traffic patterns, we simulated on-off traffic. Both busy and idle intervals follow exponential distribution with means of 10 s and 50 s respectively. The simulation time is 900 s. The simulation network has five source-destination pairs. We evaluate the packet delivery ratio, end-to-end delay and energy goodput vs. traffic load for each scheme. As shown in Fig.8, IPSM has almost the same packet delivery ratio as the normal IEEE802.11. Since, in simulations of on-off traffic, networks are less congested than those with long-lived traffic, nodes in IPSM can inform their neighbors of their awake period and the simulation result for IPSM shows a higher packet delivery ratio. The same is equally true of other protocols. However, as shown in the previous section, because NPSM cannot adapt to high traffic loads, the packet delivery ratio in NPSM is lower

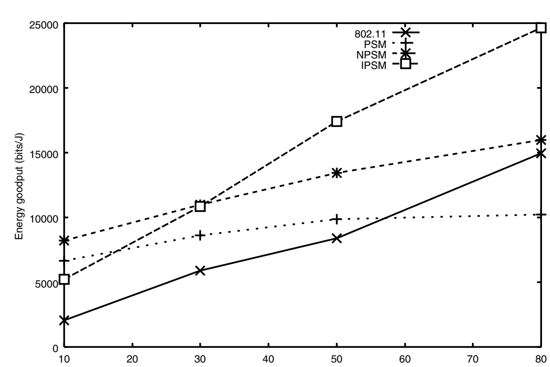

Fig. 7. Comparison of Energy goodput, 5 long-lived CBR connections

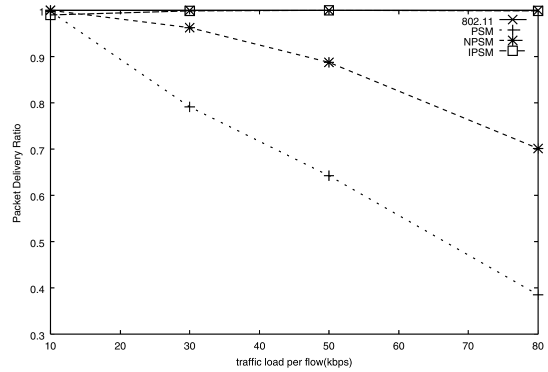

Fig. 8. Comparison of Packet delivery ratio, 5 on-off CBR connections

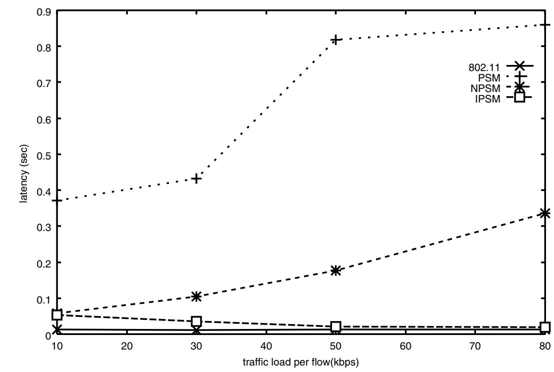

Fig. 9. Comparison of end-to-end delay, 5 on-off CBR connections

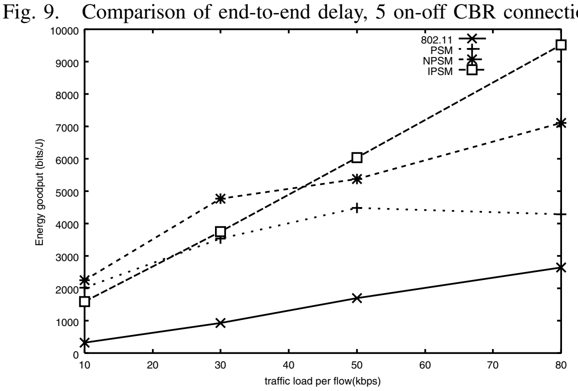

Fig. 10. Comparison of energy goodput, 5 on-off CBR connections

than in IPSM On the other hand, in IPSM, receiver nodes can stay in the awake state in the remainder of the current and the next beacon interval and wait for packet arrivals if they receive only one packet. Therefore, in IPSM the packet delivery ratio is higher. Fig.9 shows the comparison of end-to-end delay for different protocols. IPSM shows a shorter delay than other power saving mechanisms and almost the same result as the normal IEEE802.11. From this result, we find that intermediate nodes with IPSM can relay packets immediately after receiving them. The result of end-to-end delay in NPSM also shows a shorter delay than in PSM. This is because sender nodes can easily know the counter value of receiver nodes in the on-off traffic simulation, and counters in the neighbor table help each node to infer the state of neighbor nodes. However, in power saving mechanisms other than IPSM, buffered packets generate large delays as explained in the previous section. Therefore they must suffer large delays when the traffic load is high. On the other hand, in IPSM, receiver nodes can stay awake in the remainder of the current and the next beacon interval and wait for packet arrivals, if they receive only one packet. This means that in IPSM, the packet delivery ratio is higher and delay is shorter than in other PSMs. In Fig.10, we find that IPSM shows the highest energy goodput when the traffic load is high. At low rates of traffic, however, energy goodput for NPSM is higher than for IPSM because nodes in IPSM have to wait for packet arrivals, thus staying awake longer than NPSM, and NPSM can inform receiver nodes of pending packets at low rates of traffic. However, of course, nodes in NPSM cannot adapt to high traffic load.

These simulation results indicate that our proposed IPSM strongly outperforms other protocols. Furthermore, it can achieve almost the same performance with respect to delay and throughput as the normal IEEE802.11 and superior energy goodput to other power saving mechanisms.

VI. Conclusion

Ad hoc networks with power saving mechanisms developed in previous researches caused large delays and could not adapt to high traffic loads. To solve this problem, in this paper we presented an improved power saving mechanism (IPSM) which can operate only with MAC layer information. IPSM achieved shorter delay, higher throughput and high energy efficiency. Furthermore, it balanced the trade-off among these performance measures. Moreover, sender nodes in IPSM could inform receiver nodes of their awake period instead of pending packets. Consequently, receiver nodes can wait for arrivals of packets, staying awake and relay them immediately after receiving them. Simulation results showed that our proposed scheme strongly outperformed other PSMs with respect to throughput, delay and energy goodput.

Nodes with power saving mechanisms, including IPSM, must be synchronized by beacon transmissions. Since synchronization between nodes influences performances of ad hoc networks, we plan to address this problem in future research.

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