A Power Saving MAC Protocol by Increasing Spatial Reuse for IEEE 802.11 Ad Hoc WLANs

Kuei-Ping Shih, Chih-Yung Chang, Chien-Min Chou, and Szu-Min Chen

Department of Computer Science and Information Engineering
Tamkang University, Tamshui 251, Taipei, Taiwan
kpshih@mail.tku.edu.tw

***Abstract*— Scarce resources of wireless medium (e.g., bandwidth, battery power, and so on) significantly restrict the progress of wireless local area networks (WLANs). Heavy traffic load and high station density are most likely to incur collisions, and further consume bandwidth and energy. In this paper, a distributed power-saving protocol, Power-Efficient MAC Protocol (PEM), to avoid collisions and to save energy is proposed. PEM takes advantage of power control technique to reduce the interferences among transmission pairs and increase the spatial reuse of WLANs. Based on the concept of Maximum Independent Set (MIS), a novel heuristic scheme with the aid of interference relationship is proposed to provide as many simultaneous transmission pairs as possible. In PEM, all stations know when to wake up and when they can enter doze state. Thus, stations need not waste power to idle listen and can save much power. The network bandwidth can be efficiently utilized as well. To verify the performance of PEM, a lot of simulations are performed. The experimental results show that with the property of spatial reuse, PEM not only reduces power consumption, but also leads to higher network throughput in comparison with the existing work, such as DCF, DCS, and DPSM.**

I. INTRODUCTION

WLANs have been widely used recently, such as campus, hotels, and airports for internet access. However, scarce resources (e.g., bandwidth and battery energy) restrict the usage of WLANs. Besides, when the number of stations and the traffic load increase, the probability of a successful transmission will degrade and transmission collisions will increase. Transmission collisions may result in the waste of bandwidth and the consumption of energy. Therefore, how to develop a MAC protocol to increase the bandwidth utilization and reduce the energy consumption is important. This paper focuses on the bandwidth utilization and energy efficiency and proposes a MAC protocol, named PEM, to improve bandwidth utilization and increase the energy efficiency.

Power saving and power control mechanisms are two well-known mechanisms to improve power efficiency. The basic idea of power saving mechanism is to let the wireless interface of a station be turned off while the station is not going to communicate with other stations during a certain period of time. For ad hoc WLANs, IEEE 802.11 Spec. [1] provides a power saving mechanism. In addition to IEEE 802.11, there are also some researches paying their attention on power saving issue, such as [2], [3].

Power control is an alternative scheme which can improve the power efficiency. Burns et al. described the variation of power consumption regarding an Aironet PC4800 PCMCIA interface [4]. If two stations are closed enough, adjusting power level such that the receiver can exactly resolve the signal can indeed reduce the power consumption. Power control not only can save energy, but also can increase the capacity of the whole network. Fig.1 shows the so called "*channel capture*" problem [5]. The solid circle is the transmission range of station A and the dash circles are the adjusted transmission ranges of stations. Stations within the transmission range of A are all blocked due to the use of CSMA/CA mechanism when A is transmitting data to B. However, B is not so far from A. When A adjusts (decreases) its transmission power, some stations which is blocked by A will be released. Thus, C and D can transmit simultaneously when A is transmitting to B. Thus, power control is a good way to diminish the channel capture effect. The related work of power control can be found in [6], [7], [8].

Motivated by the advantages of power saving and power control approaches, we develop an efficient MAC protocol, PEM, to enhance the network utilization and reduce energy consumption. In PEM, stations can estimate their distances from the transmitter and obtain the interference relations among transmission pairs through three way-way handshaking (ATIM/ATIM-ACK/IIM). According to the interference relation, a scheduling algorithm is proposed for stations to schedule their transmissions. The scheduling algorithm can select interference-free transmission pairs as many as possible to increase the spatial reuse. Thereafter, a station intending to transmit can adjust its transmission power to transmit at its scheduled time. In PEM, all stations know when to wake up and when they can enter doze state. Thus, stations can save much power. The network bandwidth can be efficiently utilized as well. Simulation results show that PEM outperforms than existing protocols, such as DCF [1], DPSM [2], and DCS [6]. PEM not only reduces power consumption, but also increases the network throughput.

The rest of the paper is organized as follows. In Section II, we describe the background and related work about power control and power saving MAC protocols. A power saving MAC protocol by increasing spatial reuse is proposed in

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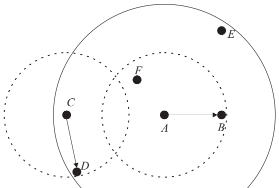

Fig. 1. The channel capture problem

Section III. Section IV shows the simulation results. Finally, Section V concludes this paper.

II. BACKGROUND AND RELATED WORK

A. Channel Propagation Model

Whether a station can correctly receive a frame or not depends on the value of signal to interference ratio (SIR) at the PHY layer. Here we use *2-ray ground reflection model* as the basic channel propagation model [9]. The received power (P_r) at distance d of the sender is calculated by

$$P_r(d) = \frac{P_s G_s G_r h_s^2 h_r^2}{d^n L}, \tag{1}$$

where P_s is the transmitted power, h_s and h_r are respectively the altitudes of the sender and the receiver, G_s and G_r are the antenna gains of the sender and the receiver, respectively, and L is the system loss. In the denominator, n is usually referred to 2 to 4 according to the distance between the sender and the receiver. We use 4 to show the channel propagation model. Here we assume all stations have the same wireless interfaces and the capability to measure the signal strength. Thus, Eq(1) can be rewritten as follows.

$$P_r(d) = \frac{c}{d^4} P_s \tag{2}$$

Eq(2) shows a simplified equation from Eq(1), where c is a constant representing all the omitted variables. If the transmission power is known in advance, e.g. the maximum transmission power (P_{max}), according to the received power (P_r), a station can calculate the distance from the transmitting station by

$$d = (\frac{P_{max}}{P_r} c)^{1/4}. \tag{3}$$

However, whether a frame can be received or not depends on SIR. Therefore, it is required to compare the received signal strength P_r and the ambient noise (P_a) received at a station.

$$SIR = \frac{P_r}{P_a} \geq SIRThres \tag{4}$$

where $SIRThres$ is an SIR threshold to distinguish a signal to be recognized as a packet or noise. Therefore, under power control, if a station use exact power to transmit to the receiver, the exact transmitting power (P_{se}) can be measured as follows. According to Eq. (4), the received power should be greater than or equal to $P_a SIRThres$. By Eq. (2), the received power is $\frac{c}{d^4} P_{se}$. Accordingly, P_{se} can be obtained as follows.

$$P_{se} \geq \frac{P_a SIRThres}{c} d^4 \tag{5}$$

In Eq. (5), d can be obtained in advance by Eq. (3), if the sender and the receiver have ever used P_{max} to exchange packets before, such as ATIM/ATIM-ACK. Replacing d by Eq. (3), Eq. (5) can be modified as below.

$$P_{se} \geq \frac{P_a SIRThres}{P_{rmax}} P_{max}, \tag{6}$$

where P_{rmax} is the received power when the sender uses the maximum power to transmit.

For simplicity, we assume that P_a is the same in the whole network. Thus, by Eq. (6), stations which had ever exchanged ATIM/ATIM-ACK in ATIM windows can use the exact power to transmit DATA/ACK after the ATIM window ends.

B. Power Saving Mechanism for IEEE 802.11

IEEE 802.11 provides a power saving mechanism. The detailed operations of IEEE 802.11 power saving mechanism please refer to [1].

Although IEEE 802.11 provides power saving mechanism, it does not take power control into account. Moreover, since IEEE 802.11 power saving mechanism requires all stations be within the communication range of each other, thus, at most one transmission pair can transmit at a time. Our proposed protocol, PEM, not only a power saving protocol, is also a power control protocol. Stations in PEM can save energy by power saving and power control. Besides, it is possible that multiple transmission pairs can transmit simultaneously due to the reduced channel capture effect resulted from power control.

C. DPSM

Another power saving MAC protocol, called Dynamic Power Saving Mechanism (DPSM), is addressed in [2]. DPSM is a modification of the power saving mechanism in IEEE 802.11. Instead of fixed ATIM window size, the main difference of DPSM from IEEE 802.11 is the dynamical adjustment of ATIM window size to adapt to the variance of traffic load.

Similarly, DPSM does not take power control into account. Of course, DPSM allows only one transmission pair to transmit at a time. However, due to the adaptation of the variable ATIM window, stations in DPSM can save more energy than stations in IEEE 802.11.

D. Distributed Cycle Stealing

In [6], an IEEE 802.11-based power control MAC protocol called DCS (Distributed Cycle Stealing) is proposed. By power control, in DCS, it is possible that transmission pairs not interfering to each other can transmit simultaneously. However, it is also possible and has high potentiality that data collisions occur among the parallel transmission pairs due to power control. On the other hand, DCS does not take power saving into consideration. Our proposed protocol, PEM, can avoid data collision of parallel transmission pairs and save much energy efficiently in comparison with DCS.

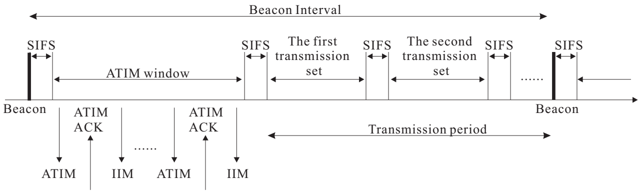

Fig. 2. The channel model and operation of PEM.

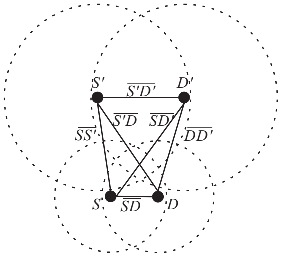

Fig. 3. The distance information what PEM need.

III. THE POWER-EFFICIENT MAC

A. *Channel Access Model and the Operation of PEM*

PEM is a distributed MAC protocol. It operates on a single-hop ad-hoc network, the same as the related works reviewed above (IEEE 802.11 power saving mechanism, DPSM, DCS). Fig. 2 shows the channel access model and the operation of PEM. Time in PEM is divided into beacon intervals. Stations in PEM announce other stations in the ATIM window and transmit data frames during the transmission period.

After a Beacon frame, each station in PEM waits for an SIFS (Shortest Interframe Space) and enters the ATIM window. Stations who want to transmit data frames have to first announce in the ATIM window. There are three basic frames in the ATIM windows: ATIM, ATIM-ACK, and IIM (Interference Indication Message) frames. If a station (we say station A) has a data frame buffered for another station (we say station B), A has to contend for the ATIM frame transmission. In the ATIM window, all stations comply with the CSMA/CA mechanism.

All stations having received the ATIM frames decode the header of the frame. B, indicating receiver of the ATIM frame, immediately replies an ATIM-ACK frame with the maximum power level after an SIFS interval. Upon receipt of the ATIM-ACK frame, A sends an IIM frame to inform all stations with the maximum power level after an SIFS interval. The gap between the transmissions of frames is an SIFS interval and all stations transmit control frames with the maximum power level during the ATIM window.

The transmission period follows the ATIM window. In the transmission period, the station which announces at the ATIM window can transmit its data frame. After an ATIM window and an SIFS interval in the beacon interval, stations begin to transmit data frames and ACK frames with the appropriate power levels. The characteristic of MIS is that all stations calculate the scheduling order and have parallel transmissions during the transmission period. The scheduling order calculate by every station is the same. This is because all stations have the same collected information during the ATIM window. After the ATIM window, the transmission pairs which want to transmit data frames stay awake in the transmission period. However, after adjusting the transmission power levels, some transmission pairs may still interfere with other pairs. MIS therefore chooses these transmission pairs to form the maximum number of transmission pairs which do not interfere with others. Some transmission pairs that would cause interference are deferred by MIS. The detail operation of MIS will be described later. The next ATIM window begins until time of transmission period is used up.

Stations may adjust their transmission power level without interfering with each other. But PEM needs some additional information before calculating the *Scheduling Order*. Fig. 3 shows what information PEM needs.

In Fig. 3, there are 4 stations in the network. Suppose *S*-*D* and *S’*-*D’* are the first and the second transmission pairs, respectively. They both have succeed in transmitting the ATIM, ATIM-ACK, and IIM frames. If PEM wants to determine that the two transmission pairs will interfere with each other or not, it has to know the following information: the distances from *S* to *D* ($\overline{SD}$ will be used in the rest of this paper), $\overline{SS'}$, $\overline{SD'}$, $\overline{S'D}$, $\overline{D'D}$ and $\overline{S'D'}$. Thus, *S’* can determine whether the transmission between *S’* to *D’* will interfere with transmission between *S* and *D* or not by $\overline{S'S}$, $\overline{S'D'}$ and $\overline{S'D}$. That is, if $\overline{S'D'}$ is smaller than $\overline{SS'}$ and $\overline{S'D}$, PEM can determine that *S’* will interfere with *S* and *D* if all of them use appropriate power levels. For the same reason, *D’* can determine if it will affect *S* and *D* by $\overline{SD'}$, $\overline{DD'}$, and $\overline{S'D'}$.

When transmitting a ATIM frame to station *D’*, *S’* only knows $\overline{SS'}$ and $\overline{S'D}$ by hearing the transmission frames of *S* and *D*. However, *S’* does not know $\overline{S'D'}$. Therefore, *S’* can know $\overline{S'D'}$ only after *D’* replies an ATIM-ACK frame. After *S’* receives the ATIM-ACK frame, *S’* can determine whether it will affect the transmission between *S* and *D* or not. Consequently, *S* has to transmit an IIM frame to inform all stations to verify whether the transmission between *S’* and *D’* will affect the transmission between *S* and *D* or not.

The distance between a transmission pair is also concerned in the ATIM-ACK frame. The distance information is used to inform all transmission pairs afterward. Besides, ATIM-ACK frames add the *IV (Interference Vector)* information. *IV* is used to record the interference information. Every station which wants to transmit an ATIM-ACK frame has to calculate whether it will affect any previous transmission pair. The information will be added into the ATIM-ACK frame. After ATIM-ACK frames, the senders also have to calculate the same information and add the information into its IIM frames. Therefore, every station will also receive this information.

Fig. 4 illustrates an example of how PEM works. Suppose that there are three transmission pairs. S_i and D_i represent the sender and the receiver of the *i*th transmission pair, respectively. For clear description, we refer S_i-D_i to the *i*th

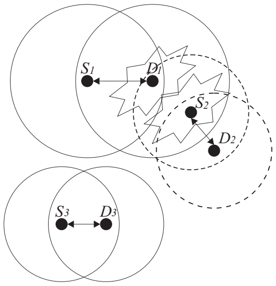

Fig. 4. After power control, the transmission of S_1-D_1 still collides with S_2-D_2.

(a)

IV1	
	S_1-D_1

(b)

IV1	IV2	
	1	S_1-D_1
		S_2-D_2

(c)

IV1	IV2	IV3	
	1	0	S_1-D_1
		0	S_2-D_2
			S_3-D_3

Fig. 5. Interference Vectors record by stations in Fig. 4. (a). No transmission happened before S_1-D_1, IV1 is empty. (b). Transmission of S_2-D_2 collides with S_1-D_1, IV2 is set "1". (c). S_3-D_3 can transmit simultaneously with S_1-D_1 and S_2-D_2, IV3 has two "0".

transmission pair. In PEM, S_1-D_1 has ATIM, ATIM-ACK, and IIM frames transmission first in the ATIM window. At this moment, stations S_2, D_2, S_3, and D_3 know that S_1 wants to communicate to D_1. S_1 and D_1 know the distance between them. Other four stations also know the distance from them to S_1 and D_1, respectively. However, no foregoing transmission of ATIM/ATIM-ACK/IIM frames was happened before the transmission of S_1-D_1. Here we use *IV* to record the interference between transmission pairs. The IV of S_1-D_1 has no record means that no transmission pair transmits control frames before S_1-D_1. Afterward is the second transmission pair: S_2-D_2. S_2-D_2 also transmits the control frames in the same manner. Because S_2 and D_2 both hear the forgoing transmission information of S_1-D_1, they could determine whether their transmission will interfere with S_1-D_1 or not. Therefore, the *IV* in the IIM frame of S_2 should record the information to indicate if transmission pair S_2-D_2 would interfere with S_1-D_1 or not.

Fig. 5(a) shows the *IV* in the IIM frame of the first transmission pair. Because no any transmission pair exists before S_1-D_1, the content of *IV* transmitted by S_1 is empty. Fig. 5(b) shows the *IV* in the IIM frame of the second transmission pair. S_2 determines that S_2-D_2 will collide with S_1-D_1. Consequently, S_2 puts a '1' in IV2 to indicate that S_2-D_2 will interfere with S_1-D_1. Here '1' represents that the interference occurred while '0' means no interference occurred. Fig. 5(c) shows the *IV* in the IIM frame of the third transmission pair. There are two "0" in IV of the third transmission pair. The above "0" represents that S_2-D_2 will not interfere with S_1-D_1. The below "0" represents that S_3-D_3 will not interfere with S_2-D_2.

IV1	IV2	IV3	IV4	IV5	IV6	IV7	
	1	0	0	1	0	0	S_1-D_1
		1	1	0	0	0	S_2-D_2
			0	0	0	1	S_3-D_3
				0	1	0	S_4-D_4
					1	0	S_5-D_5
						1	S_6-D_6

Fig. 6. Another complex example of IVs.

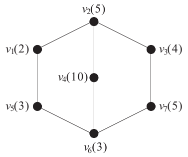

Fig. 7. An undirected graph transforms from Fig. 6.

At the end of the ATIM windows, stations involve in the control frames transmission calculate the *scheduling order* of transmissions according to the content of *IV* in the ATIM-ACK and IIM frames. Other stations that do not involve in the ATIM windows enter the Doze state for power saving. Every station computes the same scheduling order by proposed MIS algorithm. Thus, all stations after the ATIM windows will follow this same scheduling order. Stations in the transmission period transmit data frames according to the scheduling order.

B. Maximum Independent Set Algorithm (MIS)

In order to increase the throughput and to reduce the power consumption, the stations that can transmit simultaneously without interfering with each other are scheduled to transmit simultaneously. MIS tries to find the maximum number of transmission pairs without interference at the same time. The interference relation between any two transmission pairs can be obtained by listening to the IIM frames. We use an undirected graph to show the relations of all transmission pairs according to the IVs. Suppose that V and E are the sets of all transmission pairs and links in the graph, respectively. The network thus can be regarded as a graph represented as $G = (V, E)$. The vertex in V represents a transmission pair. The edge connecting two vertices represents that the two transmission pairs will interfere with each other. Fig. 6 shows an example of *IV*. Fig. 7 is the transformation of Fig. 6. Note that the suffix of a vertex in Fig. 7 represents its order of the transmission pair. The number in parentheses represents the duration of transmission.

Independent Set is a set of vertices in which there is no edge between any two vertexes. A set of vertices with no edge means the transmission pairs do not interfere with each other. $\{v_1, v_3\}$ is an example of Independent Set in Fig. 7.

MIS, Maximum Independent Set, is a set with the maximum number of transmission pairs that do not interfere with each other. One Maximum Independent Set of Fig. 7 is $\{v_1, v_3, v_4\}$.

To determine the Maximum Independent Set is an NP-complete problem [10]. We propose a heuristic algorithm

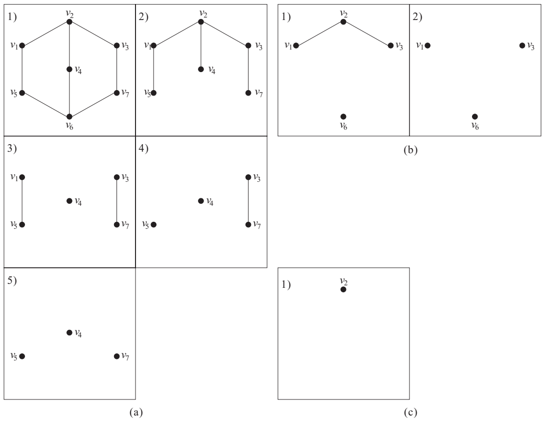

Fig. 8. The process of scheduling order by MIS. (a). The procedures of selecting the First Transmission Set. (b). The procedures of selecting the Second Transmission Set. (c). V_2 becomes the only member of the Third Transmission Set.

to obtain the Maximum Independent Set. This algorithm is specified as the following procedures. (1). Eliminating the vertex with the maximum degree of connectivities. If two vertices have the same degree of connectivities, the vertex with smaller duration will be removed. If two vertices have the same degree of connectivities and the same duration, the vertex with the small ID will be removed. (2). Repeating the above procedure until there is no edge in the graph. The remaining vertices comprise the Maximum Independent Set.

A vertex with the longest duration in the Maximum Independent Set is chosen as the *primary transmission pair*. The duration of the primary transmission pair is chosen as the duration of the Transmission Set. Other vertices eliminated repeat the two procedures above until all transmission pairs are divided into groups. MIS terminates and all transmission pairs follow the scheduling order to begin their transmissions.

In Fig. 8, we list the processes of MIS in terms of Fig. 7.

1) v_2 and v_6 both have the maximum degrees of connectivities , and the duration of v_6 is shorter than that of v_2, we eliminate v_6 and all edges connecting to v_6.
2) v_2 has the degree of connectivities 3, therefore we eliminate v_2 and all edges connecting to v_2.
3) v_1,v_3,v_5, and v_7 have the same degree of connectivities 1, and v_1 has the shortest duration, hence, v_1 and all edges connecting to v_1 are eliminated.
4) Both v_3 and v_7 have the same degree of connectivities 1. We eliminate v_3 with the shortest duration.

Now, the First Transmission Set is obtained. The duration of the First Transmission Set will be set to the longest transmission pair (i.e., v_4) in the First Transmission Set.

Fig. 8(b) and Fig. 8 (c) show the remaining results after the elimination of the First Transmission Set. MIS reruns to produce the Second and Third Transmission Set.

C. Exceptional Handling

In PEM, every station has to correctly receive all the control frames in order to acquire the distance information. However, if a station lost frames during the ATIM window, the station will have different transmission set when the MIS algorithm is performed. To avoid the situation, in PEM, we use a field, Sequence Number, in the ATIM, ATIM-ACK, and IIM frames. The Sequence Number records the transmission order of ATIM,ATIM-ACK, and IIM frames during each ATIM window. The handshake between two stations will have continuous same Sequence Numbers in their control frames. Stations know the transmission statuses of control frames by Sequence Number. Here we define two exceptional statuses during the ATIM window.

- A station who does not receive control frames in turn or does not transmit control frames in the ATIM window.
  According to the Sequence Numbers in the header of control frames, stations will know their statuses after receiving the control frames. If there exists some interference, stations may lose some control frames. By reading the header of the control frames, stations can know whether they lose the control frames or not. If a station realizes it lost some control frames, then it should keep silence during the remaining ATIM window. In other words, the station will give up to transmit and to receive while suffering the interferences which incur the losses of control frames.
- A station who misses the control frames or sets wrong Sequence Number in the header of its control frames.
  In this situation, the former stations who successfully transmit control frames will transmit an ATIM-NACK (ATIM-Negative ACK) frames in order to collide the control frames with the frames with wrong Sequence Numbers. All stations in the network cannot correctly receive the control frames with the wrong Sequence Numbers. Thus, the uniqueness of the Scheduling order is guaranteed in this manner.

IV. SIMULATION RESULTS

This section describes the simulation of PEM in comparison with DCF [1], DPSM [2], and DCS [6]. The simulation time is 10 seconds. An ATIM windows size is 20 ms and the beacon interval is 100 ms. Stations take 800 μs to transfer between the Awake state and the Doze state. Every station adopts 2 Mbps transmission rate and the transmission range of stations is 200 m. We simulate 30 stations placed randomly within a 250x250 m_2 terrain. Fig. 9 shows the throughput results of PEM, DCF and DPSM for different lambda (λ) values. Here the λ represents frames per 10 μs. We can observe from Fig. 9 that in the light load situation, PEM does not perform very well because PEM has more control frames. But with the increasing of the traffic load, PEM outperforms DCF and DPSM in network throughput due to spatial reuse.

Fig. 10 shows the mean frame delay time. Due to the MIS algorithm, the transmission of data frames in PEM would be scheduled. The transmission of data frames in PEM have small mean delay compared to DPSM and DCF. DPSM adopts variable ATIM window size. Therefore the mean delay of DPSM remains lower than that in DCF. Fig. 12 shows

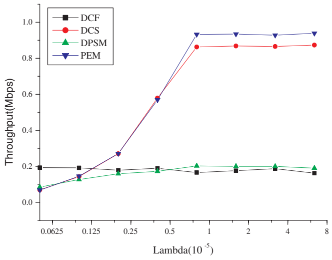

Fig. 9. The comparisons of network load and throughput in the random topology scenario.

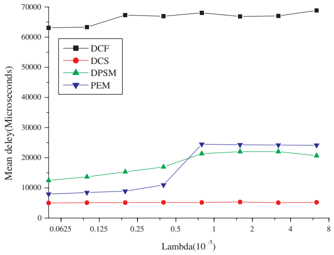

Fig. 10. The comparisons of network load and mean delay in the random topology scenario.

the control overhead . PEM adopts 3-way handshake during the ATIM window. Other protocols adapt 2-way handshake. Therefore PEM has higher control overhead. DPSM meets lower control overhead due to the variable ATIM window size. Fig. 11 shows the transmission bits per Joule. In the light load situation, PEM does not perform well than DPSM and DCF due to more control frames. However, PEM adopts power control and power saving mechanisms to improve the power throughput especially in the network with high traffic load.

V. CONCLUSIONS

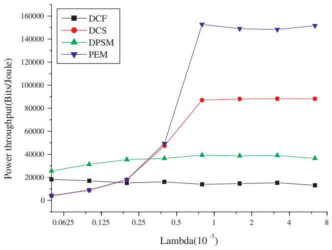

Fig. 11. The comparisons of network load and power throughput in the random topology scenario.

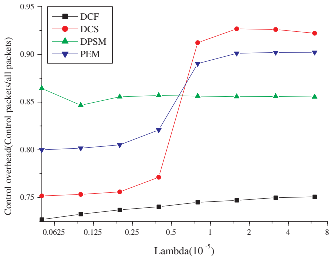

Fig. 12. The comparisons of network load and control overhead in the random topology scenario.

For the purpose of power efficiency, we devise in this paper a novel MAC protocol in which both power control and power saving mechanisms are taken into account. The former mechanism is used to reduce the unnecessary power consumption and increase the network throughput via simultaneous transmissions. The later one is used to save energy and allows the stations which do not want to transmit enter the Doze state. These two mechanisms both help the stations to save energy. Besides, adopting power control mechanism would increase the network throughput simultaneously. Simulations show that PEM outperforms in network throughput by power control via the spatial-reuse. Furthermore, PEM also reduces energy consumption as well as prolongs the network lifetime.

VI. ACKNOWLEDGEMENT

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