A Review on Energy Efficient MAC Protocols for Wireless LANs

Niranjan Kumar Ray and Ashok Kumar Turuk
Department of Computer Science and Engineering
National Institute of Technology Rourkela, Orissa-769008, India
rayniranjan@gmail.com, akturuk@nitrkl.ac.in

Abstract—**Energy efficiency is a major issue in any wireless networks. Medium access control (MAC) protocols play an important role in providing a fair and efficient allocation of the available bandwidth. Although a lot of research has been conducted on MAC protocols, the various issues involved have mostly been presented in isolation to each other. In this paper, we present a comprehensive review of energy efficiency MAC protocols for wireless LANs, integrating the issues and the challenges. We also present a classification of MAC protocols, based on the energy-efficiency, and describe them briefly.**

Index Terms—**ATIM window, beacon interval, energy efficiency, power save mode, sleep state**

I. INTRODUCTION

The popularity of wireless networks has been appreciated in the last few years due to its wide range of applicability and versatility. It has revolutionized the science and technology and added comfort and beauty to the modern life. The complex technology made simpler and more user friendly due to the amalgamation of the wireless technology with the traditional wired equipments. The wireless technology is blended with our day to day life in form of cell phone, bluetooth, pervasive computing, video conferencing, telemedicine and so on. A variety of wireless networks exists; viz. infrastructure based cellular networks, infrastructure less wireless network, and ad hoc and sensor networks [1]. Ad hoc and sensor networks have special resource requirement, which makes them different from wired networks in many aspects such as resource management, Quality of service provisioning, routing and media access control. With its significant advantages over the traditional wired network there also exist unmet challenges [2] like unpredictable mobility, restricted battery power, limited bandwidth, multi hop routing, dynamic topology, security etc. Among all these efficient utilization of energy (limited battery power) is one of the important concerns as nodes are battery operated. It is one of the very important performances metric as efficient utilization of energy increases the longevity of the network life time and hence critical in enhancing the network capacity. Energy efficiency continues to be a key factor that limits the deployability of real ad hoc and sensor networks. So efforts are made to reduce the energy consumption in different ways. It is observed that energy conservation can be done at all layer of the network protocol stack. Recently it is reported in the literature to conserve energy at different layer of the protocol stack. In this paper efforts are made to provide a comprehensive review of the state-of-art research on medium access control protocol considering energy as the major issue. The rest of the paper structured as follows. Section II focuses on cause of energy waste, energy consumption measuring and MAC classifications. Different energy efficient MAC protocols are discussed in Section III. Conclusions are drawn in section IV.

II. MAC CLASSIFICATIONS AND OTHER ISSUES

In this section we focus on causes of energy waste, energy consumption measuring and MAC classification. We also proposed a MAC classification for single and multi-hop environment.

A. Causes of Energy Waste

The major cause of energy waste at MAC layer are *collision*, *idle-listening*, *over-hearing* and *control packet overhead*. Collision occurs when the transmission packets are corrupted partially or fully. *Collision* causes retransmission thus increases the latency and power consumption. Listening to an idle channel for possible traffic is called *idle-listening.* In order to conserve energy most of the energy efficient protocols put their network interface in sleep state rather than in idle state. Receiving packets which are meant for other nodes is called *over-hearing*. *Control packet overhead* occurs when more number of control packets are used. Use of more numbers of control packets not only increase, the energy consumption but also decrease, the utilization of limited bandwidth. Carrier sensing is another major cause of energy waste due to collision of data packets and hidden and exposed terminal problems [3]. Higher bit rates and long headers also consume more power. Besides these there are many other types of energy wastes occur in wireless networks.

B. Energy Consumption Measuring

Before designing an energy efficient protocol for wireless networks, one must know the energy consumed at the network interface. The energy consumed at a network interface depends upon the node operating states. Different operating states of a node are *transmit, receive, idle* and *sleep*. Transmit and receive states are used for sending and receiving data. The default state of ad hoc and sensor network is the idle state in which network interface waits for

978-1-4244-4837-1/09/$25.00 ©2009 IEEE

possible traffic. Stemm and Karz [4] have shown that idle: receive: transmit ratios to be 1:1.05:1.4 while Freeny [5] have shown the ratio to be 1:2:2.5. This result suggests that energy consumption in the idle state cannot be ignored. The power consumption in sleep state is significantly less in comparison to the rest of the state. The Table 1 describes some experimental power consumption measurements [5] for IEEE 802.11 (2.4 GHz) interface.

TABLE 1
POWER CONSUMPTION OF DIFFERENT STATE

Interface	transmit (watt)	receive (watt)	idle (watt)	sleep (watt)	Mbps
Aironet PC4800	1.4-1.9	1.3-1.4	1.34	0.075	11
Lucent Bronze	1.3	0.97	.84	0.066	2
Lucent silver	1.3	0.90	0.74	0.048	11
Cabletron Roamabout	1.4	1.0	0.83	0.13	2

Table 1 suggests, power consumption can be reduced by putting the network interface in the sleep state for a longer time than any other state.

C. *MAC Classifications*

MAC protocols for wireless networks can be categorized into two groups: centralized MAC and distributed MAC. The figure 1 shows the MAC classification.

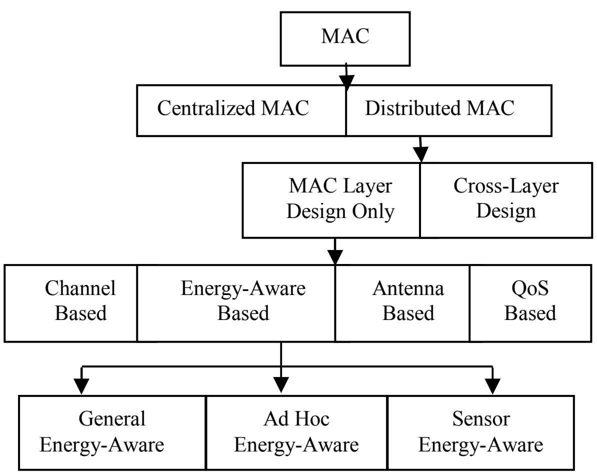

Fig. 1. Classification of MAC protocols

Centralized MAC is designed for infrastructure-based networks such as cellular network. The central entity like base station or access point collects the information from all the mobile nodes and manages the resources. It is observed that the performance of energy saving depends upon the access point capability. On other hand, distributed MAC is suitable for infrastructure-less networks like ad hoc and sensor network. Due to the absence of central controller, distributed MAC [19], [24] is more challenging than the centralized MAC in many aspects. An extensive study is going on the distributed MAC to improve its performance and overcome its potential challenges. Cross layer design (CLD) [20], [23] is another potential area of studies in MAC layer.

III. Energy Efficient MAC Protocols

The discussion in the section includes only the energy efficient distributed MAC protocols without considering cross layer design protocols. Energy efficient MAC protocols can be classified into three different categories viz. general energy-aware, ad hoc energy-aware and sensor energy-aware as shown in the figure 1. We discusses IEEE 802.11 power save (PS) mode and its variants [21] in sub-section A, energy-efficient MAC protocols for mobile ad hoc network (MANET) in sub-section B and sub-section C describes energy efficient wireless sensor network (WSN) protocols.

A. *IEEE 802.11and its Variants*

This sub-section describes the power management in IEEE 802.11 [6] and other protocols.

1. IEEE 802.11 Power Save Mode

IEEE 802.11 DCF has two types of power save modes. One for infrastrure based network where the access point buffers the MAC service date unit (MSDU) when the nodes are in PS mode and transmits them at designated time by the help of traffic indication map (TIM) and delayed traffic indication map (DTIM). The limitation of this mode is that its efficiency depends upon the access point capacity. This type of power saving mechanism is not suitable for ad hoc and sensor network environment.

On the other hand IEEE 802.11 IBSS PS mode is for infrastructure less network which is relevant to ad hoc model. Synchronized beacon intervals are established by the node which initiates the IBSS and is maintained in a distributed fashion. It also defines the fixed size length *announcement traffic indication message* (ATIM). All the nodes wake up at the beginning of the *beacon interval* (BI) and remain awake till the end of the ATIM window. The nodes participating in the traffic announcement remain awake till the end of BI and the non-participators go to sleep state at the end of the traffic window. The effectiveness of power saving depends upon the value selected for the ATIM window and BI. If the ATIM window is too short then not enough traffic will be announced during this period. Similarly if the window is too large then wake up time for entire nodes will be more which will lead to undue consumption of energy. In the same way if the BI is too long more nodes will announce more traffic and more numbers of nodes will be activated after the end of the ATIM window and there will be increased contention due to increased number of nodes trying to transmit at each interval.

Power saving mechanism is the main criteria in evaluating an energy efficient protocol, but factors like latency and throughput also to be taken into consideration. The amount of energy save due to sleep state is also affected by the cost of transition from sleep to wake up state, length of the BI and ATIM window, and the network traffic and mobility model. Simulation results presented by Hagen Woesner et al. [7] suggests that short beacon interval gives superior energy saving but it reduces the throughput. This is true for small network with light traffic load. For a network with moderate to heavy load longer beacon interval gives better result. A general observation suggests that some throughput can be compromised in order to get higher energy saving. That means it is manageable if 30% or more energy are conserved at a cost of 10% or less throughput at a moderate traffic load. Figure 2 shows the data transmission in IBSS PS mode**.**

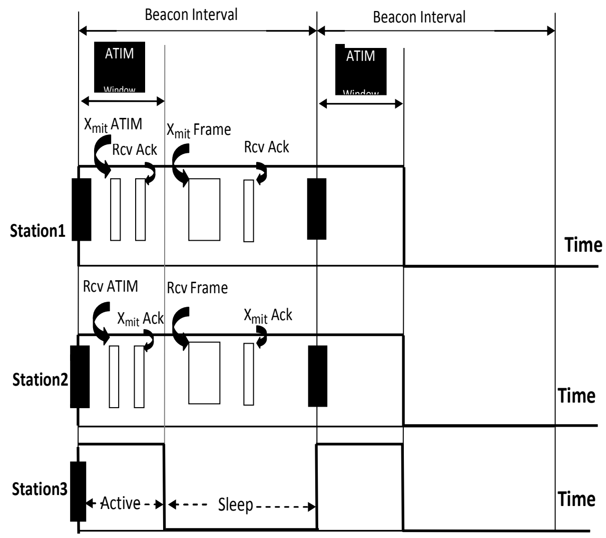

Fig.2. Data transmission in IBSS PS Mode

2. EC-MAC: Energy Conserving MAC

Energy conservation is the major design criteria in EC-MAC [8]. It also support different traffic type and provide different levels of service quality for bandwidth allocation. The protocol is based on a combination of reservation and scheduling mechanisms. The mobile nodes are controlled by the base station and transmissions are organized by the same in term of frames. Each frame consists of fixed number of slots. The frame is started by frame synchronization message (FSM), which contains synchronization information. The protocol has different phase viz. request/update phase, new user phase, downlink and uplink phase. The *request/update phase* reduces the collision. *New user phase* which is variable in length allow user registration with the base station. This phase is operated in contention mode using slotted aloha protocol. *Down link and uplink data phase* reduces turnaround time and collision. For the concern of battery power conservation, request/update phase should not be operating in contention mode. It was designed for infrastructure based wireless networks but can be extended to ad hoc networks by selecting a node to act as a coordinator in a distributed fashion. The energy efficiency of EC-MAC in comparison with other protocols provide better power saving. Simulation results presented in [8] shows that at heavy traffic load its power saving is very close to IEEE 802.11 PS mode.

3. Dominating-Awake-Interval protocol

IEEE 802.11 PS mode is applicable for single-hop fully connected network. Its power saving mechanism is not suitable for multi-hop networks and is based on clock synchronization. In multi hop network like ad hoc networks, achieving clock synchronization is a difficult task due to its unpredictable mobility and communication delay. In *dominating-awake-interval* [9] protocol redesign the IEEE 802.11 PS mode for multi hop networks. The protocol is based on multiple beacons and overlapping awake intervals. The beacon interval contains three windows called active window, beacon window and MTIM window. Beacon window and MTIM window are part of the active window as shown in the figure 3(a). During active window a node switches on its radio receiver for listening and sending the packets. Beacon window is used for sending its own frame where as it receives the beacon frame from other nodes through MTIM window. MTIM window is similar to ATIM window of IEEE 802.11 PS mode. Within each beacon, the lengths of all three windows are constant. When a node decides to enter the PS mode, it divides its time axis into fixed length beacon intervals, the sequence of beacon intervals are alternatively labeled as odd and even intervals as shown in the figure 3(b). In the odd beacon interval the active window is started with beacon window followed by MTIM window and in even beacon interval the active window is terminated by beacon window always. In the figure 3(b) it is found that node A can respond node B in even beacon interval and vice-versa in odd beacon interval. Beacon intervals are alternatively designed as even and odd, so that both the node can able to access each other.

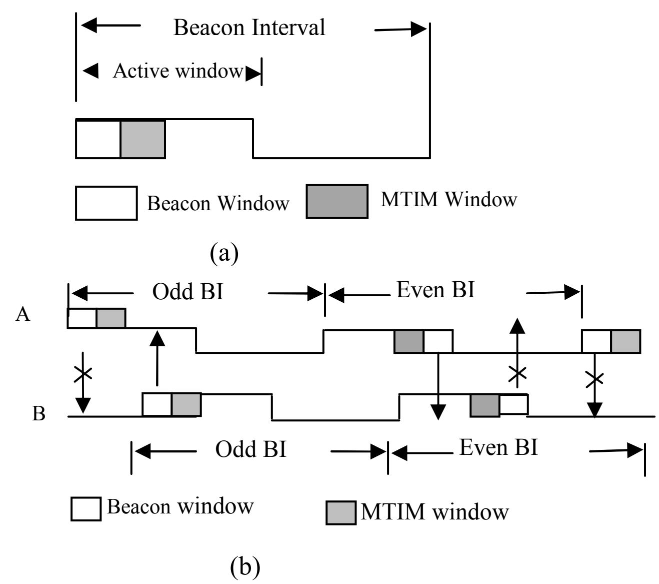

Fig.3 Structure of beacon interval (a) active window,beacon window and MTIM window (b) even and odd beacon intervals in Dominating-Awake-Interval protocol

4. Dynamic Power Saving Mechanism (DPSM)

It is a variance of 802.11 DCF power save mode. It uses the concept of ATIM window and beacon intervals. During ATIM window all nodes are awake and the nodes having no traffic to receive or send go to sleep state. The limitation of fixed ATIM window is already discussed in IEEE 802.11 PS mode. The work reported in [5] shows that if ATIM window is fixed then performance as well as energy saving gets affected. DPSM [11] improves the performance by using the variable ATIM window. It allows the sender and receiver node to dynamically change their ATIM window. The window size increased when some packets are pending after the current window is expired. Data packet carries the current length of the window and the nodes which overhear this modify their window length. This allow the sender and receiver go to sleep state immediately after their transmission is over. Performance of DPSM is better compared to IEEE 802.11 PS mode in term of power saving, however it is more complex in implementation.

B. Energy-Efficient MAC protocols for MANETs

Mobile Ad Hoc Networks (MANET) [1] is a collection of mobile nodes with no pre-established infrastructure. A large degree of freedom and self organizing capability makes MANET completely different from other networks. It is one of the challenging and more innovative areas of wireless networking. It is basically a peer-to-peer multi-hop mobile wireless network where information packets are transmitted in a *store and forward* manner from a source to an arbitrary destination via intermediate nodes. It has many applications in different areas such as disaster management, rescue operation, vehicular network and many more. Ad hoc networking improves the efficiency of fixed and mobile internet access and enables totally new applications such as sensor and mesh networks. Like all other wireless networks energy conservation is a major issue in MANET as well. Few of the MANET protocols are discussed below.

1. PAMAS: power aware multi-access protocol with signaling for ad hoc networks

Energy efficiency is the primary goal in PAMAS [10] and is achieved by using two separate channels one for control and other for data. It uses RTS/CTS mechanisms and these signals are transmitted over the control channel while the data are transmitted over the data channel. Node with packets to transmit, sends a RTS over the control channel, and waits for CTS. If no CTS arrive then the node enters a back-off state. However, if CTS is received, then the node transmits the data packets over the data channel. The receiving node transmits a “busy tone” over the control channel for others to determine that the data channel is busy. The use of control channel allows nodes to determine when and how long to power off. If a node has no packets to transmit, that node ought to power itself off. Similarly, if at least one neighbor of a node is transmitting and another is receiving, the node ought to power off because it cannot transmit or receive a packet even if it’s transmit queue is non-empty. The power off time of a node is determined through its control channel. If it receives a control packet which is not meant for it, will be power off for that particular period. After the off period when it wakes off it will access the media through its data channel and if it knows multiple transmission is going on it utilizes probe protocol to decide about the power off period. Simulation results presented in [10] show that power saving varies from 10% to 70% depending upon the network types. PAMAS is most effective in networks with high density and traffic load. Power saving ideas of PAMAS can be incorporated to other protocols without affecting delay and throughput performance.

2. Power Control MAC (PCM)

PCM [12] achieves energy saving without causing throughput degradation by implementing different types of transmission power. DATA and ACK packets are sent using minimum transmission power while RTS/CTS packets are sent with maximum transmission power. When a node sends RTS, it transmits with maximum power P_{max} and this value is included in the control packet. Receiver measure the incoming strength of the control signal then it calculate the noise level of its surrounding and computes the minimum necessary power level at which sender must transmitted. This value is included in the CTS packets. The sender receives the CTS along with maximum power level of receiver. On hearing this transmission, the neighboring nodes differs their transmission. During data transmission same procedure is used between sender and receiver with minimum required power level that should be enough for the transmission of DATA as well as ACK.

The limitation of PCM protocol is that, it requires an accurate estimation of received packet signal strength and factors like multipath propagation, fading and shadowing effects may degrade its power saving performance.

3. Power Control Multiple Access (PCMA)

PCMA [13] uses two channels one for sending busy tone and the other for sending data and acknowledgement signal. The power control mechanism is used for increasing channel efficiency through spatial frequency reuse. Rather than using RTS/CTS signal it uses two signals *request-power-to-send* (RPTS) by sender and *accept-power-to-send* (APTS) by receiver to determine the minimum transmission power that will be enough for successful packets reception at receiver. These two signals are transmitted over data channel after this real data transmissions as well as acknowledgement are received on the same channel. Every receiver sets up a special busy tone as a periodic pulse to avoid interference with neighboring node. Collisions are resolved by backoff strategy as in IEEE 802.11.

PCMA enhanced aggregate channel utilization by more than a factor of two as compared to IEEE 802.11.

C. Energy-efficient MAC Protocols for WSN

Energy-efficiency is a major design goal for wireless sensor networks (WSN) [22]. Two commonly used access principles in sensor networks are contention based and scheduled based. In the former nodes contend for the channel whenever they have data to send. *Carrier sense multiple access* (CSMA) based techniques are used to prevent collisions. In other hand scheduled based protocols divides the time into different time slots and allocate these to all nodes within the transmission range to each other. A scheduler collects all time slot allocation requests and distributes them to transmitters and receivers. Some of the protocols combine advantages of both categories. We are presenting few sensor network protocols here.

1. Sensor-MAC(S-MAC)

Energy conservation and self configuration is the primary goals of S-MAC [14]. It is a contention based protocol. The design overview includes periodic listen and sleep which is similar to PS mode of IEEE 802.11. In S-MAC listen time is fixed and depends upon the contention window and radio bandwidth. Sleep interval can be changed according to requirements. Nodes can exchange their schedule by periodically broadcasting a 'sync' packet to their immediate neighbor; it uses the concepts of message passing to minimizing the communication overhead. For collision avoidance S-MAC implements the concepts of physical and virtual carrier sense by the help of network allocation vector (NAV). S-MAC uses sleep schedule to reduce the energy waste caused by idle listening. Low duty cycle operation is achieved by periodic sleeping. It enables each node to adaptively switch according to traffic in the network. Figure 4 shows the messaging scenario of S-MAC.

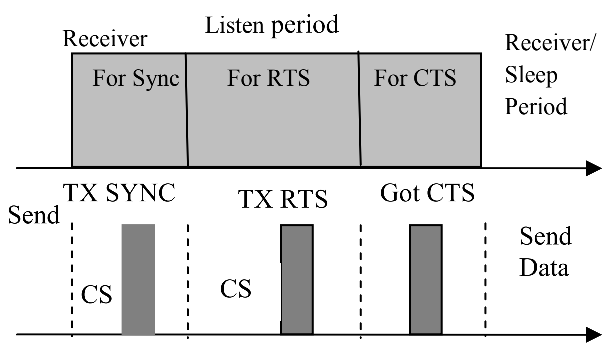

Fig.4. S-MAC Messaging Scenario

2. Timeout-MAC (T-MAC)

Like S-MAC energy conservation is the main design issue of T-MAC [15] protocol. It addresses the energy conservation by idle listening more effectively than S-MAC. Periodic listen and sleep methods used by S-MAC performs poorly in variable network traffic. It overcomes this by time out scheme. If a node does not listen anything during the threshold value then it goes to sleep state to save energy. A node also goes to sleep state after overhearing the RTS/CTS destined for other node. But the nodes can miss other RTS/CTS while it is in sleep state as well as it can disturb some communication while wake of. An early sleeping problem arises when the traffic through the network is mostly unidirectional such as communication to sink node. The problem is node goes to sleep when a neighbor still has some message left. This problem occurs in asymmetric communication pattern. T-MAC solves this problem in two ways. First method called *future-request-to-send* (FRTS) and second method is called *full-buffer priority*. In FRTS if a node over hears CTS it immediately send FRTS. The node getting FRTS knows that some traffic is pending for it so it will not go to sleep mode. The limitation with this scheme is that it increases the overhead in light network traffic. When a nodes buffer is full it prefers sending rather than receiving. This is the concepts of *full-buffer-priority*. When a node receives a RTS signal it sends RTS to other nodes rather than sending CTS. This technique is not ideal in high-load. A simulation result shows that FRTS mechanism increases maximum throughput by approximately 75% without consuming more energy. Figure 5 shows the FRTS methods.

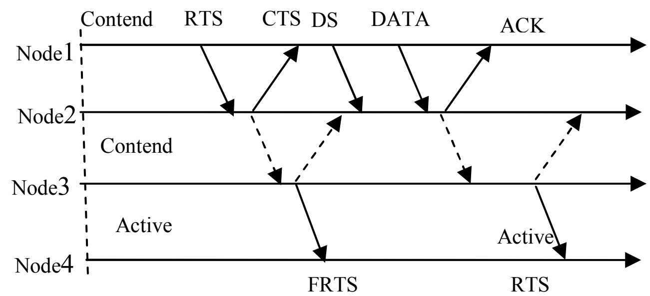

Fig.5. Future-Request-To-Tend methods in T-MAC

3. Traffic-Adaptive MAC (TRAMA)

TRAMA [16] attempts to reduce energy consumption caused by collisions. It is a scheduled based protocol in which time is divided into random access and schedule access. In random access periods each node has knowledge of all two-hop neighbors and exchange neighborhood information with each other by the help of a *neighbor protocol* (NP). *Schedule exchange protocol* (SEP) is used to transmit schedule information as well as actual data packets during schedule access time. By the help of NP and SEP nodes determine their radio state using the *adaptive election algorithm* (AEA). In AEA each node calculates a priority for itself and all two-hop neighbors using a hashing function of the current slot. Node then sends the data when it has the highest priority in the slot. Similarly If one of its neighbors has the highest priority and the node determines that it should be the intended receiver through information acquired during SEP, it sets itself to the receive mode otherwise it turn to sleep state to conserve energy. As distributed election algorithm are used to elect one transmitter within each two-hop distance which eliminates the hidden terminal problems.

The advantage of TRAMA is that probability of collision is less as a result more energy is conserved. However the computation at each node increases as each node to calculate priorities of its two-hop neighbors in each time slot and duty cycle of the nodes increase in random time periods.

4. Z-MAC: A Hybrid MAC for Wireless Sensor Networks

It combines [17] the advantage of contention based protocols and scheduled based protocols. It does not require much infrastructure support, clock synchronization and global topology information. Each node runs a distributed scheduling algorithm called DRAND (distributed RAND) [18], to assign time slots to every node in the network. Time slots are assigned at deployment and are reassigning only when significant change in topology occurs. After deployment each node runs a neighbor discovery protocol by passing message to its one-hop neighbor. The message contains current list of one-hop neighbor of the sender. The objective of neighbor discovery protocol is to provide two-hop neighborhood information to each node. After the neighbor discovery is over, *time frame* rule defined by the DRAND guarantee that, only one node in a two-hop neighborhood will own a time slot in every frame. Two types of contention levels, are used by transmission control phase, they are *low contention level* (LCL) and *high contention level* (HCL). Contention states are used for channel utilizations and fairness purpose. A node changes its state from LCL to HCL when it receives an *explicit contention notification* (ECN) from a two-hop neighbor and once again returns back to original state after the specific ECN time (t_{ECN}) is over. LCL works like CSMA based protocol while HCL is similar to TDMA based protocol. ECN message are sent by the owner when of the slot contention level is high. The advantage of ECN message is that it removes the hidden terminal problem and increases the channel utilization.

IV. Concluding Remarks

This paper is a review on the recent works published on "Energy efficient MAC protocols for Wireless LANs". Few of our observations are mentioned below.

(i) IEEE 802.11 PS mode is one of the most popular energy efficient protocol and have been appreciated by majority of studies; however its variant for multi-hop network yet to prove its excellencies.

(ii) A sleep state is used as one of the main stay of power saving by majority of energy efficient protocols, but the degradation in throughput is one of the major challenges need to be taken care of, and

(iii) All most all the protocols are layer based and increase in layering increases overhead which in turn hampers the energy efficiency. So integration of layering is a potential area of further study.

Acknowledgment

Authors would like to thank the anonymous reviewers for their constructive comments on the manuscripts. This work was supported by Department of Information Technology, Govt. of India under the grant no: 13(1)/2008-CC&BT.

References

[1] C.E. Perkins, "Ad Hoc Networking," *Addison Wesley*, 2001.

[2] R. Ramanathan and J. Redi, "A Brief Overview of Ad Hoc Networks: Challenges and Directions," *IEEE communication magazine*, pp. 20-21, May 2002.

[3] A. Tsertou and D.I. Laurenson, "Revisiting the Hidden Terminal Problem in a CSMA/CA Wireless Network," *IEEE Transactions on Mobile Computing*, vol. 7(7), pp. 817-831, October 2008.

[4] M. Stemm and R.H. Katz, "Measuring and reducing energy consumption of network interface in handheld devices," *IEICE Transaction on communications*, E80-B (8), pp. 1125-1131, August 1997.

[5] L.M. Freeny, "Energy efficient communication in ad hoc networks," *Mobile Ad Hoc Networking,Wiley-IEEE press*, pp. 301-328, 2004.

[6] IEEE 802.11 Working Group, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, 1999".

[7] H. Woesner, J.P. Ebert, M. Schlager, and A. Wolisz, "Power saving mechanisms in emerging standards for wireless LANs: The MAC level perspective," *IEEE Personal Communications*, vol. 5(3), pp. 40-48, June 1998.

[8] K. Sivalingam, et al., "Design and analysis of low-power access protocols for wireless and mobile ATM networks," *ACM/Baltzer Journal on Wireless Networks (WINET)*, Special Issue on Advances in Wireless Systems, vol. 6(1), pp. 73-87, February 2000.

[9] Yu-Chee Tseng, Chih-Shun Hsu, and Ten-Yueng Hsieh, "Power-Saving Protocols for IEEE 802.11-Based Multi-Hop Ad Hoc Networks," *Computer Networks: The International Journal of Computer and Telecommunications Networking*, vol. 43(3), pp. 317-337, October 2003.

[10] S. Singh, and C.S. Raghavendra, "PAMAS - power aware multi-access protocol with signaling for ad hoc networks," *ACM Computer Communication Review*, July 1998.

[11] E.S. Jung and N.H. Vaidya, "An energy efficient MAC protocol for wireless LANs," *IEEE INFOCOM*, June 2002.

[12] E.S. Jung and N.H. Vaidya, "A Power Control MAC Protocol for Ad Hoc Networks," *ACM Intl. Conf. Mobile Computing and Networking (MOBICOM)*, pp. 37-47, September 2002.

[13] J. Monks, V. Bharghavan, and W. Hwu, "A Power Controlled Multiple Access Protocol for Wireless Packet Networks," *IEEE INFOCOM*, vol. 1, pp. 219-228, April 2001.

[14] W. Ye, J. Heidemann, and D. Estrin, "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE/ACM Transactions on Networking*, vol. 12(3), pp. 493–506, June 2004.

[15] T.V. Dam and K. Langendoen, "An Adaptive Energy- Efficient MAC Protocol for Wireless Sensor Networks," *1st ACM Conf. Embedded Networked Sensor Sys.,* Los Angeles, CA, November 2003.

[16] V. Rajendran, et al. "Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks," *Proc. ACM SenSys '03, Los Angeles, CA*, pp. 181–92, November 2003.

[17] I. Rhee, et al. "ZMAC: a Hybrid MAC for Wireless Sensor Networks," *SenSys'05,* San Diego, California, USA, pp. 90-101, November 2005.

[18] I. Rhee, A. Warrier, and L. Xu, "Randomized dining philosophers to TDMA scheduling in wireless sensor networks," *Technical report,* Computer Science Department, North Carolina State University, Raleigh, NC, 2004.

[19] W.Wang, V. Srinivasan, and K. Chua, "Power Control for Distributed MAC Protocols in Wireless Ad Hoc Networks," *IEEE Transactions on Mobile Computing*, vol. 7(10), pp. 1169-1183, October 2008.

[20] X. Lin, N.B. Shroff, and R. Srikant, "A Tutorial on Cross-Layer Optimization in Wireless Networks," *IEEE Journal on selected areas in communications*, vol. 24(8), pp. 1452-1463, August 2006.

[21] M. Ilyas, "The Handbook of ad hoc wireless networks," *CRC Press,* 2003.

[22] A. Swami et al., "Wireless sensor networks: signal processing and communications perspectives," *John Wiley & Sons Ltd*, 2007.

[23] E. Setton, et al., "cross-layer design of ad hoc networks for real-time video streaming," *IEEE Wireless Communications*, vol. 12(4), pp. 59-65, August 2005.

[24] H. Shan, W. Zhuang, and Z. Wang, "Distributed Cooperative MAC for Multihop Wireless Networks," *IEEE Communications magazine,* vol. 47(2), pp. 126-133, February 2009.

.