BLAM: An Energy-Aware MAC Layer Enhancement for Wireless Adhoc Networks

Sameh Gobriel, Rami Melhem and Daniel Mossé
Computer Science Department, University of Pittsburgh
{sameh, melhem, mosse}@cs.pitt.edu

***Abstract*—*In wireless adhoc networks channel and energy capacities are scarce resources. However, the design of the IEEE 802.11 DCF protocol leads to an inefficient utilization of these resources. In this paper we introduce BLAM, a new Battery Level Aware MAC protocol, which is developed from an energy-efficiency point of view to extend the useful lifetime of an adhoc network. We modify the IEEE 802.11 DCF protocol to enable BLAM to dynamically tune the transmission probability and the random deferring time for fresh and collided data packets based on the node's current relative battery capacity. We show that BLAM can achieve an increase of 15% in the total network lifetime and an increase of about 35% in the total number of received packets. We also show that BLAM is backward compatible with the currently deployed IEEE 802.11 MAC protocol.*

I. Introduction

An *adhoc network* is an infrastructureless multi-hop wireless network in which all devices establish direct communication with other nodes without a centralized entity. Adhoc networks have a significant impact on many military and civilian applications, such as combat field surveillance, security and disaster management, data gathering, and virtual meetings and conferences.

The wireless network hosts have *finite* battery supply and in many cases the nodes are installed in an environment where it may be hard (or undesirable) to retrieve them to change or recharge the batteries. It is crucial to design techniques to reduce the energy consumption by the wireless hosts. The network nodes need to be energy conserving so that total time in which the network is connected and functioning is maximized.

IEEE 802.11 standard [15] defines a distributed random access MAC protocol called Distributed Coordination Function (DCF), which is based on the mechanism of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). DCF uses a binary exponential backoff (BEB) algorithm to resolve channel contention and incorporates the use of the RTS/CTS method to resolve the hidden terminal problem. A lot of prior work [1], [2], [3], [6], [24], [26] evaluated the performance of the IEEE 802.11 DCF via simulation and theoretical analysis.

Recent research has investigated energy conserving mechanisms and various approaches have been proposed for each layer of the communication protocol stack [17] to reduce the energy consumption. As mentioned in Section III, many efforts are in the direction of designing new energy efficient medium access protocols. However, our work does not propose a new protocol but rather slightly enhances the already widely deployed IEEE 802.11 to include energy-aware measures. Our enhancements are backward compatible with the existing protocol.

This work is based on the observation that the IEEE 802.11 standard can operate very far from optimality, and much channel bandwidth and energy are wasted in collisions and collision resolutions. Moreover, when a basic energy efficient scheme is used in which control frames (RTS/CTS) are sent with maximum power and data frames with a reduced power, this effect is magnified because the control frames are the ones that faces collision and not the data frames. This motivates us to propose a new power-aware enhancement for the IEEE 802.11 to try to save and conserve both the nodes energy and

This work has been supported by the Defense Advanced Research Projects Agency through the PARTS (Power-Aware Real-Time Systems) project under Contract F33615-00-C-1736 and by NSF through grant ANI-0125704.

the channel capacity wasted in collisions.

Toward this goal, we introduce a *Battery Level Aware MAC* (BLAM) which tunes the transmission probability and the random deferring time for both fresh packets and collided ones based on the node's current relative battery capacity. Consequently, BLAM prohibits the low energy nodes from contending for medium access with the high energy nodes, and thus saves the energy of these critical nodes and consequently extends the network lifetime.

The rest of the paper is organized as follows: Section II reviews the basic operation of the IEEE 802.11 protocol.Section III presents related work and different power control schemes at the MAC layer. Sections IV explains the details of BLAM. Section V describes the energy model used and the simulation environment. Simulation results are presented in Section VI. We conclude the paper in Section VII.

II. Overview of IEEE 802.11 DCF Protocol

IEEE 802.11 DCF [15] defines two access methods: *basic access method* and *RTS/CTS* access method. The basic access method involves only DATA/ACK exchange, in which data packets are transmitted when channel access has been obtained. ACK frames follow successful data packet receptions. The RTS/CTS mechanism is mainly used to minimize the amount of time wasted when a collision occurs and to address the *Hidden Terminal* problem [6] [1]. In the RTS/CTS access scheme, when a node wants to send packets to another node, it first sends an RTS (Request to Send) packet to the destination after sensing the medium to be idle for a so-called DIFS interval. When the destination receives an RTS frame, it transmits a CTS frame immediately after a so-called SIFS interval. The source station is allowed to transmit its data frame only if it receives the CTS correctly. If the CTS is not received by the source station, it is assumed that a collision occurred and an RTS retransmission is scheduled. After the data frame is received by the destination station, an acknowledgment frame is sent back to the source verifying successful data reception.

Nodes overhearing RTS, CTS, data or ACK packets have to defer their access to the medium. Each host maintains a *Network Allocation Vector* (NAV) that records the duration of time during which it must defer its transmission. The NAV value is updated each time a station overhears a valid MAC frame. Figure 1 illustrates the operation of the IEEE 802.11 DCF.

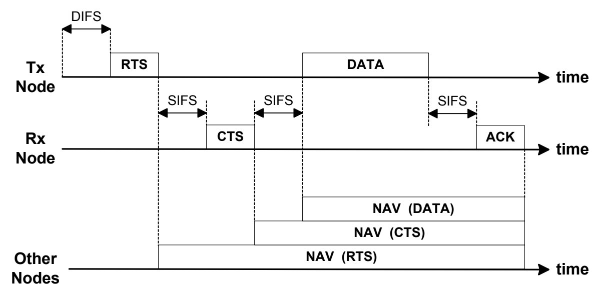


Fig. 1. IEEE 802.11 DCF Operation

The use of the RTS/CTS mechanism helps to minimize the duration of collisions and the collisions caused by hidden terminals. The successful exchange of small messages, RTS and CTS, reserves the medium within the range of the receiver and the sender for the intended transmission period guaranteeing undisturbed transmission for longer data frame. Clearly, if a collision occurs with two or more small RTS frames, the time loss is smaller compared to the collision of long data frames. On the other hand, RTS/CTS decrease the efficiency since it transmits two additional frames without any payload. Consequently, the IEEE 802.11 standard defines a parameter called *RTS-Threshold*, that indicates the data length under which the data frames should be sent without RTS/CTS. The *RTS-Threshold* parameter is not fixed in the standard and has to be set separately by each station.

A collision occurs when two or more stations within the transmission range of each other transmit simultaneously in the same time slot. As a result, the transmitted packet is corrupted and the colliding hosts have to schedule a retransmission after deferring for a period randomly chosen in the interval $[0\,..\,(CW-1)]$, where CW is the current value of the contention window of the node.

The value of CW depends on the number of failed

[1]This problem arises when two stations that are not in direct radio contact with each other try to transmit to a third station that is within the transmission range of both of them

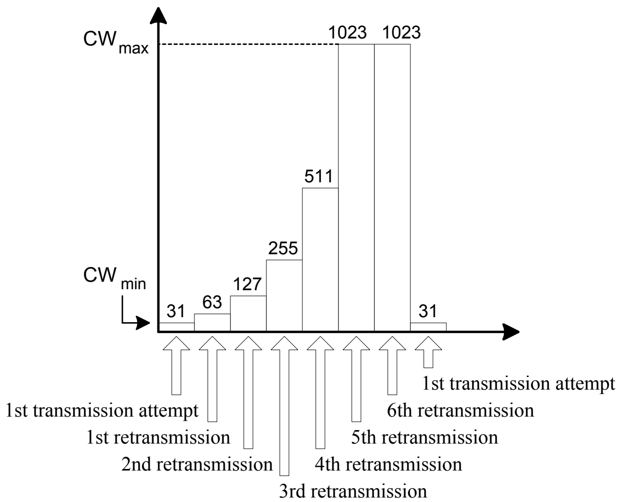


Fig. 2. Exponential Increase of the CW

transmissions of a frame. At the first transmission attempt, CW is set equal to CW_{min} , that is, the minimum contention window size. After each retransmission due to a collision, CW is doubled, up to a maximum value $CW_{max} = 2^m \cdot CW_{min}$, where m is the maximum number of retries. Once the CW reaches CW_{max}, it will remain at this value until it is reset. The CW is reset to CW_{min} after every successful transmission of a data frame or when the maximum number of retries is reached and the data packet is discarded. Figure 2 illustrates the increase of the contention window using an exponential back-off mechanism.

III. Related Work

Recognizing the challenge of energy consumption in ad-hoc networks, much research has been directed toward the design of energy aware protocols. We can categorize the previous research work on power-aware MAC layer into three categories, *Reservation Based Power-Aware MAC*, *Switching Off Power-Aware MAC* and *Transmission Power Control*.

a) The Reservation Based Power-Aware MAC: tries to avoid collisions in the MAC layer, since collisions may result in retransmissions, leading to unnecessary power consumption. The EC-MAC [23], presented the idea of applying reservation schemes in wireless networks MAC protocols for energy conservation. Although EC-MAC was originally constructed for networks with base stations serving as access points, its definition could be extended to adhoc networks, where a group of nodes may select some type of coordinator to perform the functions of a base station, as proposed in [4] and [20]. Furthermore, because the coordinator can consume the resources of certain nodes, a group of schemes were proposed in which the coordinators are rotated among network nodes. In [14] coordinators are randomly chosen, however, in [13], the remaining battery capacity controls the probability of the coordinator selection.

b) The Switching off Power-Aware MAC: tries to minimize the idle energy consumption by forcing nodes to enter the *doze* mode. For example, PAMAS [22], allows a station to power its radio off when it has no packet to transmit/receive but has to keep a separate channel on which the RTS/CTS packets are received. Similarly, Chiasserini [5] allows a station to go to sleep, but a special hardware, called Remote Activated Switch (RAS), is required to receive wakeup signals. Also, in [27] the geographical area is partitioned into smaller grids in each of which only one host needs to remain active to relay packets for all the stations in the same grid. Furthermore, Pattem [19], discussed various activation strategies for the nodes, including Randomized, Selected and Duty-cycle modes. In Randomized activation mode the nodes are activated in a random pattern. In Selected activation, nodes are switched on based on the activity region. However, in Duty-cycled activation nodes are turned on periodically.

c) Transmission Power Control: came about because the maximum power in the wireless card is consumed during the transmission mode. Much research has been proposed to minimize the transmission power and thus maximize the network lifetime. According to the path-loss radio propagation model there is the non-linear relation between the transmission power and the the transmission distance. It is always more energy conserving to send the data in a multi-hop fashion using relay nodes rather than sending it directly to the destination. PARO [12], for example, favors forwarding the data to the nearest neighbor until reaching the destination than sending the packets to a further neighbor and thus saves the transmission energy.

A simple power control scheme for the 802.11

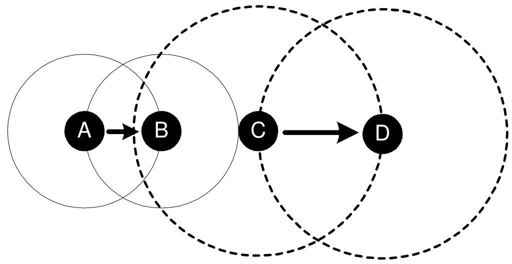


Fig. 3. Hidden Terminal Jamming Problem

RTS/CTS protocol should adjust the transmission energy for data and control frames (RTS/CTS) according to the distance between the sender and the relay node. However, as shown in Figure 3, different power levels among network nodes introduce asymmetric links, a problem known as the "Hidden Terminal Jamming" problem [25]. A hidden node C not sensing an ongoing low power data transmission, can corrupt the data packets being sent from A to B by concurrently transmitting a message to node D. Therefore, as depicted in Figure 4, the control frames have to be transmitted using a high power level, while the DATA and ACK are transmitted using the minimum power level necessary for the nodes to communicate [11] [21].

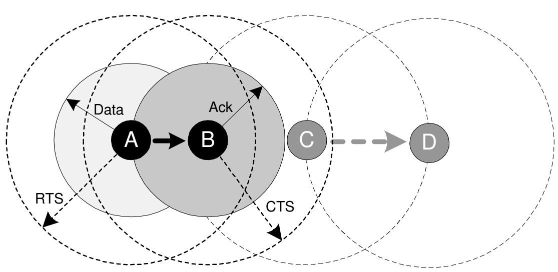


Fig. 4. Control Frames with Maximum Power

Other protocols control the transmission power not only based on the distance between the sender and the receiver but also based on different channel conditions. For example, the scheme presented in [21] adjusts the transmission power according to the SNR at the receiver. It allows a node, A, to specify its current transmit power level in the transmitted RTS, and allows the receiver node, B, to include a desired transmit power level in the CTS sent back to A. However, although reducing the transmission power can result in energy savings, it can also result in a higher bit error rate (BER). The higher the BER the higher the number of retransmissions is, which might increase in the overall network energy consumption. Therefore, based on that observation, the protocol in [7] chooses an appropriate transmission power based on the packet size.

IV. Battery Level Aware MAC (BLAM)

A. Motivation

In WLANs, the nodes included within the coverage area of a certain host may send control messages that collide with the RTS/CTS frames transmitted by this node. A collision resolution scheme (exponential backoff) is applied whenever a collision is detected. The higher the number of collisions the lower the network throughput is and the higher energy is consumed resolving these collisions.

The situation might be worse in a multihop wireless adhoc network, because each message is forwarded in more than one hop. Consequently, a message potentially encounters collisions at each hop throughout the whole route from the source to the destination. As a result, the total number of collisions increases and more channel bandwidth and energy are wasted.

On the other hand, in a power-aware adhoc network, a basic power control scheme favors transmitting the data to the nearest neighbor instead of transmitting it to a further one to conserve the transmission power. Accordingly, the power-aware route will be composed of a big number of shorter hops causing the number of collisions and retransmissions to increase more. Furthermore, as mentioned in the Section III, a smarter power aware scheme will transmit the short control frames using a higher power than the data frames [11] [21]. However, the drawback of this power-aware schemes is that the control frames are the ones that face collisions and the ones being retransmitted using the high transmission power. Thus, the collision effect on the total energy consumption is much worse than first thought.

Based on the above observations, BLAM conserves the channel bandwidth and the energy consumption by decreasing the total number of collisions in an adhoc network. As discussed later, this is done by modifying the random access nature of the IEEE 802.11 DCF to a prioritized access protocol, where the priority of the node to access the medium is determined by its remaining relative battery capacity.

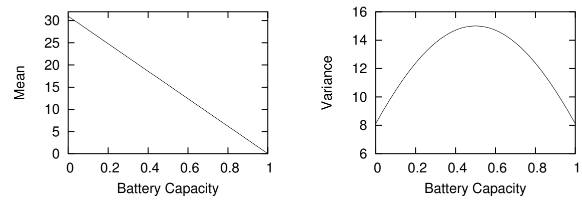
Furthermore, in IEEE 802.11 DCF, all nodes involved in a collision are equally treated and all of them attempt retransmissions in subsequent time slots after applying the random backoff algorithm. Thus, it is possible that energy-poor nodes waste additional energy in subsequent unsuccessful attempts because they are contending with the high-energy nodes for channel access. From the network lifetime point of view, the low energy nodes are the most important and most critical nodes. These nodes have used their energy either because they have a lot of data to send or because they are nodes located in the confluence of many routes in the network. Leaving these critical nodes to deplete their energy may cause a *partition* of the network and some sources might be unable to reach other destinations. On the other hand, the energy wasted in collisions and collision resolutions will not be so significant on the high-energy nodes. Thus, it is unfair to let the low energy nodes contend with the high energy nodes on channel access. BLAM propose a a new partitioning philosophy so that the nodes are split into virtual groups according to the amount of residual battery energy left. As a result, the simultaneous contention of low and high-energy nodes is restricted.

B. Modifications to IEEE 802.11 DCF

BLAM modifies the IEEE 802.11 DCF in two ways, changing the transmission probability for fresh data packets and changing the distribution of the random deferring time after an unsuccessful transmission attempt. As depicted in Figure 1, in IEEE 802.11 DCF, if a fresh data packets arrives at a node's transmit buffer, the node first senses the medium, if it is found idle for a DIFS interval, the node sends an RTS. BLAM, on the other hand, sends the RTS with a probability that depends on the current relative battery capacity of the node. The probability for transmission is obtained from a normal distribution whose mean and variance are functions of the relative battery capacity (as depicted in Figure 5):

$$\begin{aligned} Mean &= CW_{min} \cdot (1 - R_i) \\ Variance &= \frac{CW_{min}}{2} \cdot cosine\left(2 \cdot \left|\frac{1}{2} - R_i\right|\right) \end{aligned} \quad (1)$$

where CW_{min} is the minimum contention window size, and R_i is the relative battery capacity of node i.



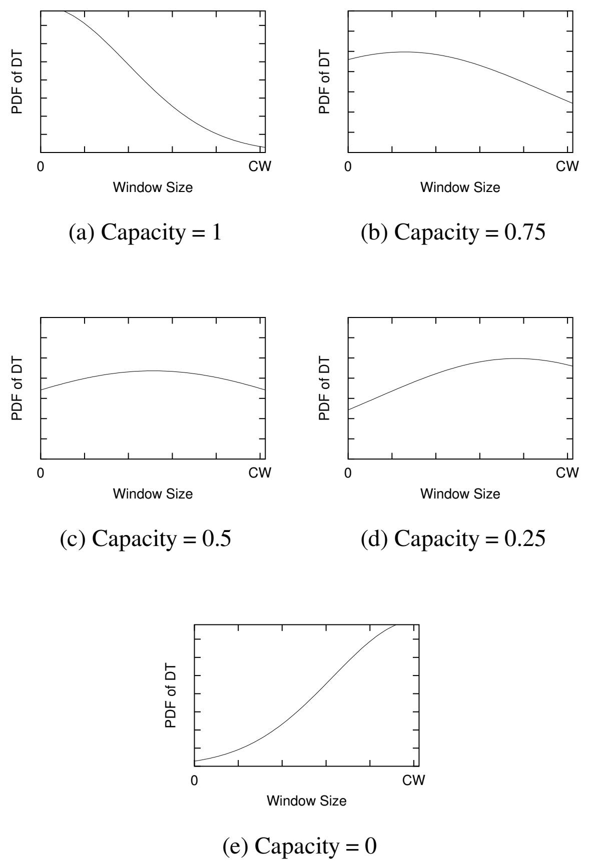
(a) Mean (b) Variance

Fig. 5. Mean and a Variance of the Normal Distribution for Probability of Transmission as functions in battery capacity

Furthermore, in IEEE 802.11 DCF, when a collision is detected, the collided hosts schedule a retransmission after deferring for a period that is randomly chosen in the interval $[0..(CW-1)]$, where CW is the current size of the contention window. In BLAM, when two or more stations collide, each station chooses to schedule its retransmission after a random amount of time. The random deferring period is picked up from a normal distribution that is defined in the interval $[0..(CW-1)]$. However, the mean and variance of the deferring time distribution are as given by Equation 1, replacing CW_{min} with the contention window size CW.

Figure 6 depicts the normal distribution from which the deferring time is determined at different relative battery capacity levels, ranging from full to empty capacities. It should be noted that, similar to the IEEE 802.11 DCF, the value of CW depends on the number of retransmissions. Initially CW will be set to the minimum contention window size CW_{min}, then at each unsuccessful transmission attempt the value of CW will be doubled.

As shown in Figures 5 and 6 and as expressed in Equation 1, for the full battery capacity nodes the mean of the normal distribution is at 0. As the battery capacity decreases, the value of the mean increases. When the node consumes all its residual energy the distribution mean will be at CW. The motivation



(a) Capacity = 1 (b) Capacity = 0.75

(c) Capacity = 0.5 (d) Capacity = 0.25

(e) Capacity = 0

Fig. 6. Deferring Time Distribution with a Variable Mean and a Variable Variance

for such design is to assign a priority for each node based on its residual energy.

When a node has full capacity, the distribution of the random deferring time will be as shown in Figure 6(a). As a result, it is most probable that a high-energy node will pick a short deferring time rather than picking a longer one. A short deferring time means that these nodes will have more chance to access the channel and thus have a higher priority. As the node residual energy starts decreasing, the mean of the normal distribution will start moving to the left, as shown in Figures 6(b), 6(c) and 6(d), causing the probability of choosing a longer deferring time to increase. A low-energy node will have the mean close to the Contention Window size (CW), as depicted in Figure 6(e), and thus these nodes will pick longer deferring time and will have less chance to access the medium and a low priority.

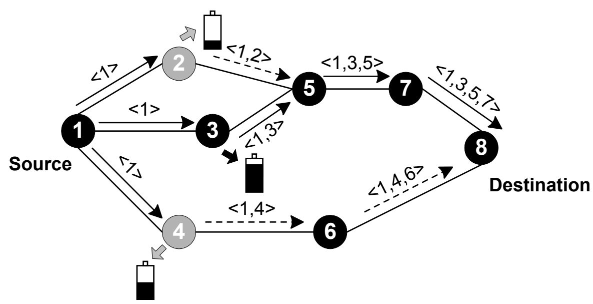
A similar thesis holds for the transmission probability of fresh data. When fresh data arrives at a high-energy node, the waiting time before attempting to transmit a frame will have similar distribution to that given in Figure 6 (with CW set to CW_{min}). Therefore, a high-energy node will most probably wait a shorter period of time than a low-energy one before attempting to transmit the newly arrived frames. As a result, the transmission probability of fresh data will be higher in the high-energy nodes and will decrease as the node consumes its battery capacity. Accordingly, the priority of the node will be proportional to its residual energy.

In that manner, the network nodes are divided among a *continuous* set of priority classes based on their left energies. The probability of contention for channel access will be higher among the members of the same class as they have a higher probability to pick comparable values for the deferring time and for the transmission probability. However, the contention between nodes from different classes for medium access is less probable. Consequently, low-energy nodes will not waste their scarce energy colliding with high-energy nodes and thus, the useful network lifetime is extended. Moreover, each class of nodes will eventually gets its share to access the channel based on its assigned priority. Therefore, the frames transmission attempts are distributed in time causing the total number of collisions to be reduced and the energy wasted in collision to be conserved.

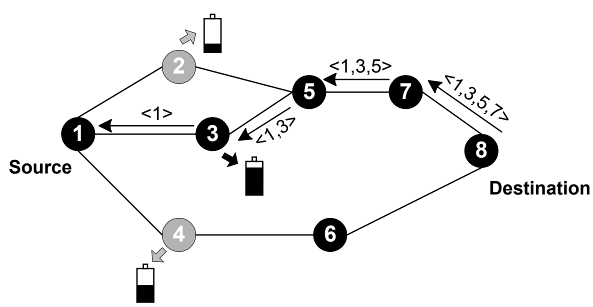
It should be noted that, as given by Equation 1, the variance of the distribution for the fresh data transmission probability and for the deferring time distribution is also a function in the node remaining energy. As shown in Figures 5 and 6, at low and high remaining capacity the variance of the distribution is smaller than that defined at the mid-range battery capacities. The reason behind such design is that the mid-range energy nodes constitutes the majority of nodes in an adhoc network, having a small variance will enforce these hosts to choose comparable values for the waiting time before attempting to transmit (or retransmit) a packet and hence the total number of collision will increase. As shown in Figure 6(c), for a mid-range energy node the distribution will be very close to a uniform distribution; therefore, the majority of nodes access trials will be widely distributed. On the other hand, the variance for the high-energy and low-energy nodes is small to separate as much as possible these two classes of contending nodes.

C. Routing Issues

Although BLAM does not waste the battery capacity of the energy-poor nodes in contending with the high-energy ones, it might seem unfair because low-energy nodes are assigned a low priority and will have a lower chance to access the channel. However, the unfairness to low energy nodes is intentional and is designed in such a way to further extend the network lifetime.



(a) Route Request Propagation



(b) Route Reply from Destination

Fig. 7. Route Discovery Operation

When the energy-poor nodes have a lower chance to access the channel, they will have longer delays and will be conceived by the network layer as *congested* nodes. As a result, the network layer will invalidate the routes passing through these low-energy nodes and will try to bypass them by redirecting the data to other available routes. Accordingly, the scarce battery capacity of the low-energy critical nodes will be only used in transmitting the nodes own data and not to forward other nodes' message. It should also be noted that when a *Route Request* is transmitted, the low-energy nodes will have a lower chance to access the medium and most probably will be unable to send a *Route Reply* back to the source node. As a result, the low-energy nodes will have less probability to participate in new forwarding routes. The routing layer will bypass the route that passes through these critical nodes to another route that might have longer delay but will last for a longer period and thus extend the network lifetime.

This idea is depicted in Figure 7, where *Node 3* has a higher battery capacity than both *Node 2* and *Node 4*, thus *Node 3* has a higher probability to access the channel than the other two nodes. Consequently, *Node 3* is able to forward the *Route-Request* from the source to the destination and the *Route-Reply* message in its way back faster than the other nodes. As a result, this node will be selected to participate as a forwarding node in the route between the source and the destination, which conserves the energy of the other two critical nodes.

D. Discussion

The effectiveness of BLAM is because of the following reasons. First, BLAM can be easily incorporated in the widely used IEEE 802.11 MAC. BLAM does not require any additional fields to be added to the existing MAC layer frames. It also does not require any changes in the frame formats or in the way the frames are handled by the network interface card during transmission, reception or forwarding. The required modifications can be implemented as an open loop control circuit that takes the node energy level as an input and generates a normal distributed random number, based on the discussed specifications, to control the transmission probability and the random deferring time. Moreover, no specific support or changes are required at an upper protocol layer (routing layer) or at a lower one (physical layer).

Secondly, BLAM is *backward compatible* which means that an adhoc network node that uses BLAM can be deployed in a network that uses the traditional IEEE 802.11 MAC protocol without needing any changes.

Finally, BLAM modifies the transmission probability and the deferring time distribution based on the local host state. BLAM does not require any communication with a centralized controlling host and does not need any global information from neighbor nodes. Therefore, there is no need to send any new messages to neighbor nodes (to poll the nodes status), as these *Request-Status* messages and their replies might increase the network load and wastes the channel bandwidth and the hosts energy.

V. Energy Model and Simulation Environment

Different assumptions about the radio characteristics, including energy dissipation in transmission, receive, idle and sleep modes have been made in many research works. For example, measurement results reported in [10] provide detailed information on the energy consumption of the wireless interface cards (Lucent WaveLAN 802.11 PCMCIA "Silver" and "Bronze" NIC), running in an adhoc mode configuration. Similar results are also reported in [8] [9], where the power consumption measurement results of an Aironet PC4800 PCMCIA NIC are presented. To illustrate this issue, Table I summarizes the results from [9].

TABLE I
Aironet PC4800 Wireless Interface Card Power Consumption

	Sleep	Idle	Tx	Rx
MAC	5	40	125	125
Baseband	2	23	33	100
IF Modem	10	10	400	500
Freq. Synth.	0.075	0.075	40	40
RF/IF converter	0.05	0.05	300	100
Low noise amp.	off	35	0ff	35
RF power amp	off	off	1600	off
max. total power	≈ 20	≈ 110	≈ 2500	≈ 900

It is apparent from Table I that the maximum power consumption in a wireless card occurs during the transmit mode. However, the power dissipated in the receive mode cannot be neglected and is comparable to the transmission power consumption. On the other hand, based on the fact that in an adhoc network a considerable portion of the network lifetime is typically consumed in transmitting, forwarding and receiving data between nodes, the idle and the sleep energy consumption are low enough to be neglected. It should be mentioned that the network interface card is in *idle* mode when the card is not transmitting or receiving any packets but all its internal circuits are powered on, while the *sleep* mode is when some of the card circuits are powered off.

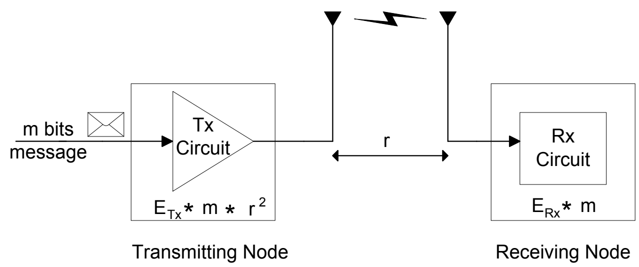


Fig. 8. Wireless Card Energy Consumption Model

In our simulation analysis we use the model described in Figure 8, to evaluate the energy consumed in a wireless network interface card. Based on this model the energy required to transmit a packet from node A to node B is the same as the energy required to transmit from node B to node A (*Symmetric Channel* assumption). As depicted in Figure 8, the energy model takes into consideration both the transmission energy and the receive energy. We assume that the transmission energy depends on both the message length and the distance of transmission while the receive energy is only dependent on the message length. The values of the coefficients in both the transmit and the receive case are derived from the properties of the Lucent WaveLAN 802.11 PCMIA network interface card [10].

In our analysis we used the *Network Simulator* (NS2) [18] to simulate a network that covers an area of $1000 \times 1000 m^2$, with 60 nodes randomly distributed in this area. The adhoc network simulated is fully connected (i.e., any source can reach any destination) and the maximum transmission range of a single node is 150 *m*. A total number of 50 flows (i.e., 50 source/destination pairs) are generated, each flow is assumed to be a constant bit rate (CBR) flow over an UDP connection. Each flow has the rate of 2 packets/source/sec and the packet size is 512 bytes. The value of the *RTS-Threshold* is set to zero, default NS2 value, which means that the RTS/CTS scheme is enforced for every packet.

For each flow the source and the destination are randomly chosen from the total set of nodes. Any node can be a source or a destination for one or more message flows. Dynamic Source Routing (DSR) [16] is used as the routing protocol at the network layer. The total simulation time is 1600 seconds, the flow sources start transmitting at a time that is randomly chosen from the start of simulation time up until 800 seconds. A flow stops transmitting at a time that is uniformly distributed between the flow start time and the simulation end time. Initially, all the nodes are assumed to have full battery capacity of 5 joules at the start of the simulation. The maximum transmit power of a node is assumed to cover the whole transmission range (150 m). The receive power is assumed to be approximately 45% of the maximum transmit power. We note that the results presented here will be conservative, since we are assuming such high receive power. If we considered the Aironet card (from Table I with receive power at 36% of maximum transmit power), the performance of BLAM would show even higher gains. This is because the savings of BLAM is proportional to the ratio of the transmit energy to the total energy consumption (in other words, BLAM saves on transmit energy).

In our analysis we compared BLAM to the basic IEEE 802.11 MAC protocol at two cases. First, when a *Power-Management* scheme is applied where the control frames (RTS/CTS) are sent with maximum power while the Data/ACK frames are sent with a power that is proportional to the square of the distance between the sender and the receiver. Second, at a *No-Power-Management* case when all the MAC frames are sent with the maximum transmit power. Different simulation parameters are summarized in Table II.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of Simulation runs	10
Network Size	$1000 \times 1000\ m^2$
Node range	150 m
Node initial energy	5.0 J
Number of connections	50
Packet Size	512 bytes
Transmission rate per source	2 pkts/sec
Simulation time	1600 sec

VI. SIMULATION RESULTS

In our simulation analysis, we compared BLAM with two version of the IEEE 802.11 DCF. The first version is the basic protocol, as defined in Section II, we call it *Basic 802.11*. The second version, which we call *Modified 802.11*, applies one modification to the basic protocol: when a fresh data packet arrives at a network node, it first senses the medium for a period of a DIFS, if found idle, the station waits a random amount of time uniformly distributed in the interval $[0..(CW_{min}-1)]$ before attempting to transmit this frame.

The following metrics are used to evaluate the performance of the different MAC layer protocols:

- *Network lifetime* which we define as the time duration from the beginning of the simulation until the first instant when the First Node Dies (FND).
- *Number of dead nodes* we define a dead node as a sender nodes whose battery capacity is below the level needed to transmit one packet or a receiver node whose battery capacity is less than that required to receive a single packet.
- *Number of collisions* denotes the number of dropped control frames due to a collision. At a single collision event there are two or more colliding hosts, counting the number of dropped frames is equivalent to counting the number of nodes participating in each collision.
- *Number of received packets* denotes the number of correctly received data frames that successfully arrived at their final destination. The number of correctly received data packets reflects the total network throughput.
- *Number of transmitted packets* denotes the total number of data and control packets that were transmitted in the network, which includes those that are correctly received or those that are dropped.

As previously mentioned, two sets of simulations are performed. First, when using a basic power management scheme that transmits the control frame with maximum power while the data/ack frames are transmitted with a reduced power. Second, when no power management is applied where all the MAC frames are transmitted with maximum power.

A. *Performance with Power Management*

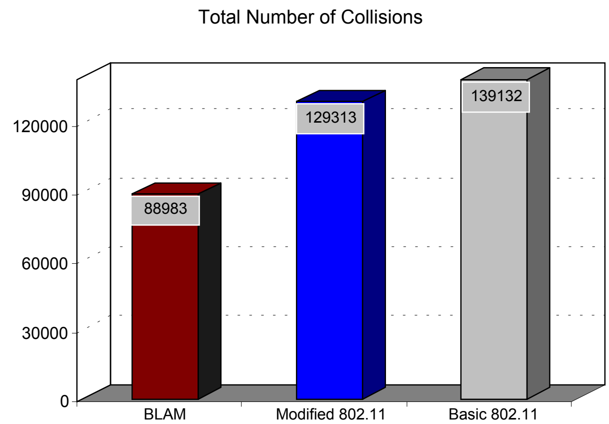


Fig. 9. Total Number of Collisions with Basic Power Management

Figure 9 compares the total number of collisions in the adhoc network for the period of the network lifetime when the basic power management protocol is used. As shown in Figure 9, BLAM successfully decreased the total number of collisions by 36% over the Basic 802.11 and by 31% over the Modified 802.11. At the start of simulation, all the nodes will have full capacity and the distribution presented in Figure 6 will have a small variance, therefore, it is more selective and the nodes will pickup comparable values for the transmission probability and for the random deferring time. As a result, initially the number of collisions faced in BLAM should be higher than that faced in the Basic 802.11 or the Modified 802.11. However, once a node is able to access the medium its energy is consumed in transmitting the data frames and will move towards another priority class where there is no contention, thus, the node will be able to send its data packets with less collision.

When the number of collisions is reduced in the network, less energy is wasted in collision, collision resolution and retransmission. Thus, the network lifetime will be longer. Moreover, as previously discussed, the prioritized nature of BLAM restricts contention between high-energy nodes and low-energy nodes and hence the useful lifetime of the network is extended, as shown in Figure 10. When comparing

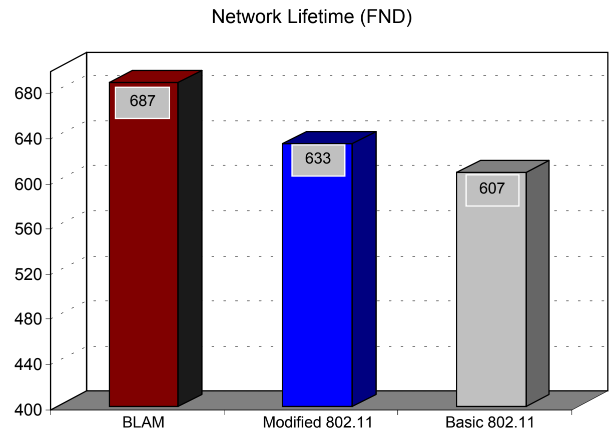


Fig. 10. Network Lifetime with Basic Power Management

the time up until the first node dies in the three protocols, the lifetime for BLAM is 15% more than that of the Basic 802.11 and 9% more than the Modified 802.11.

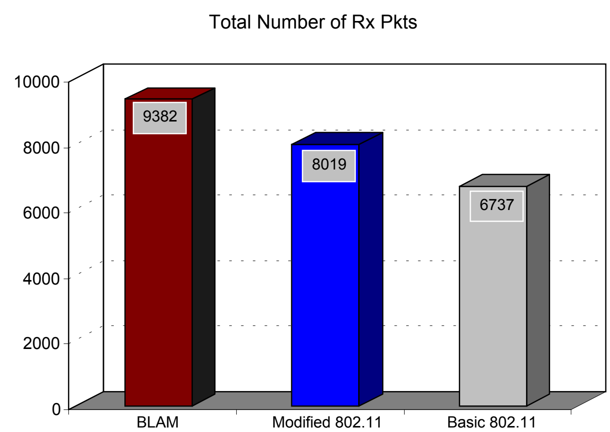


Fig. 11. Total Number of Received Packets with Basic Power Management

Decreasing the number of collisions and increasing the network lifetime can be done trivially by forcing the nodes to send less data. However, this scheme is useless because the number of received packets is reduced. Figure 11 represents the comparison between the total number of data packets that are correctly received at their final destination in the three MAC protocols. As shown in Figure 11 BLAM increased the total number of received data packets by 39% over the Basic 802.11 and by 16% over the Modified 802.11.

Although BLAM was able to deliver more data packets to its final destination, the total number of

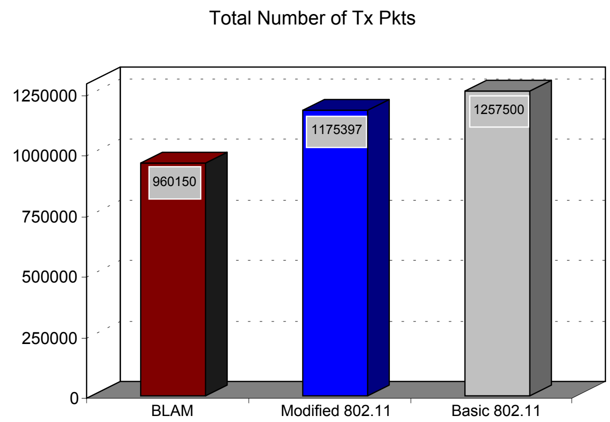


Fig. 12. Total Number of Transmitted Packets with Basic Power Management

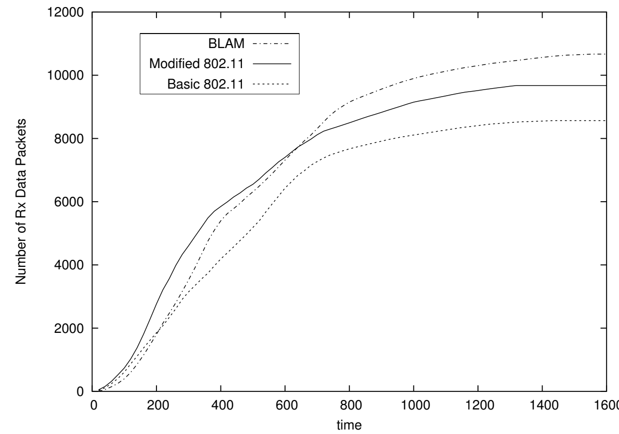


Fig. 14. Number of Received Packets versus Time when using Basic Power Management Scheme

transmitted packets in BLAM is less than that in Basic 802.11 and in the Modified 802.11 as shown in Figure 12. This is based on the fact that in BLAM the number of collisions is reduced, thus, a lower number of packets is dropped and hence the number of packets retransmitted will be smaller.

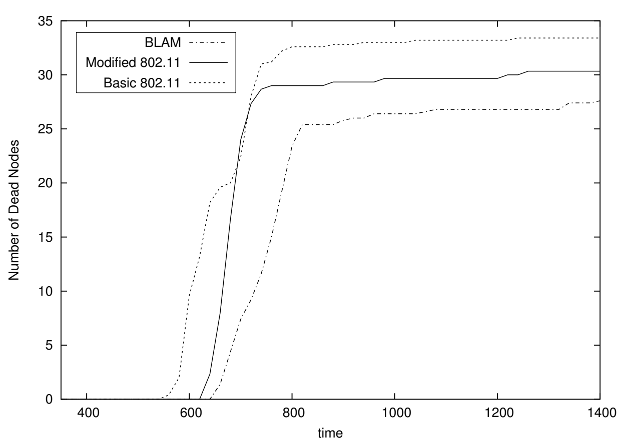


Fig. 13. Number of Dead Nodes versus Time when using Basic Power Management Scheme

Figure 13 represents the total number of dead nodes in the network as a function of time. Since BLAM conserved the energy of the critical nodes, less nodes will die and the rate of node death will be lower than that in the Basic 802.11 and the Modified 802.11, as depicted in Figure 13. Furthermore, the total number of dead nodes at the end of simulation is much smaller in the BLAM than the Basic 802.11 and Modified 802.11 cases.

Figure 14 represents the accumulated number of the correctly received data packets versus time. As shown, BLAM was able to deliver more packets to its final destination than the other protocols. However, towards the end of the simulation, a lot of the network nodes are dead, therefore, many of the routes in the network are broken and no data packets can make through from their sources to the destinations. The network throughput is defined as the total number of received packet divided by the time. Consequently, the network throughput can be seen as the slope of the curve shown in Figure 14. Towards the end of the simulation the curve in Figure 14 flattens which indicates that the throughput of the network is zero and hence no more messages are being received.

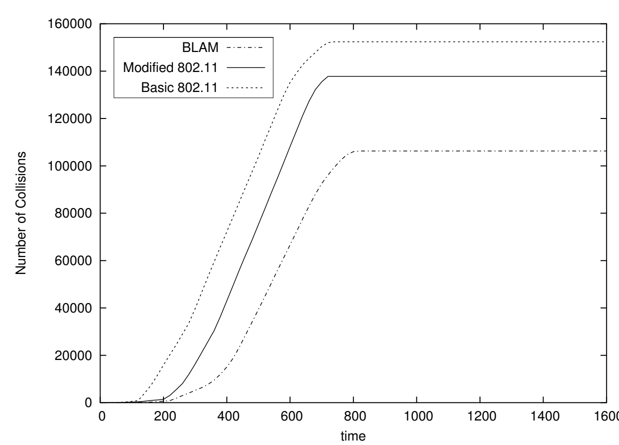


Fig. 15. Number of Collisions versus Time when using Basic Power Management Scheme

Figure 15 represents the accumulated number of collisions faced in the adhoc network versus time. As shown in Figure 15 the total number of collisions in a network that uses BLAM is much less than that using the IEEE 802.11 DCF. It should be mentioned that, towards the end of the simulation, a lot of the network nodes are depleted from their energy and are among one priority class which might increase in the contention probability. However, this effect is insignificant because it occurs when almost all the routes in the network are broken and no packets can be transmitted.

B. *Performance without Power Management*

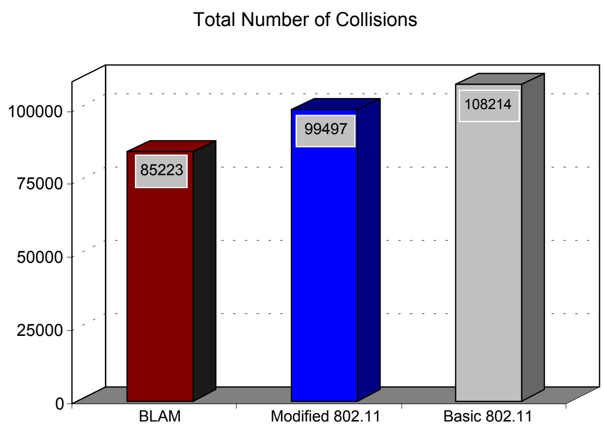


Fig. 16. Total Number of Collisions with No Power Management

Figure 16 compares the total number of collision faced in the adhoc network when no power management protocol is used. As shown in Figure 16, and similar to the results previously presented, the number of collisions faced when using BLAM is much less than that when using the IEEE 802.11 DCF. BLAM decreased the total number of collisions by 21% over the Basic 802.11 and by 15% over the Modified 802.11. The percentage difference is smaller than the case when using the power management scheme because the network lifetime is shorter and hence the total number of packets transmitted (and accordingly the number of collisions) is lower.

When *No Power Management* scheme is used, both the Data/ACK frames and the RTS/CTS frames will be sent with maximum power. However, the length of the DATA frames is much larger than that of the control frames and hence the energy consumed in transmitting the data frames will be much larger than that used to transmit (or retransmit) the control frames. It is evident that, reducing the num-

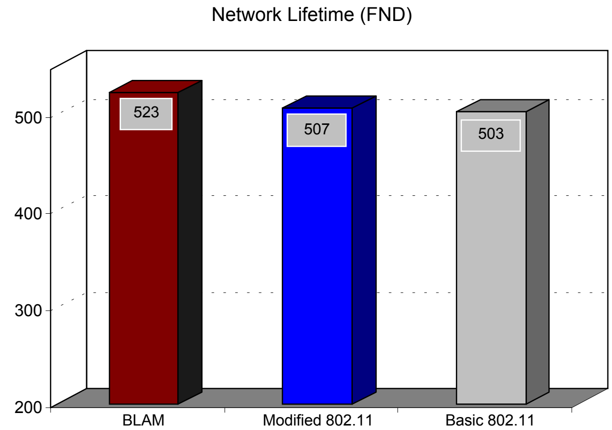


Fig. 17. Network Lifetime with No Power Management

ber of collisions will not make a big difference in the network lifetime because the most of the energy is consumed in transmitting the long data frames. As a result, and as reflected in Figure 17, the gain in the network lifetime when using BLAM will be smaller than when a power management scheme is used. BLAM extended the useful lifetime of the network only by 4% over the Basic 802.11 and by 3% over the modified 802.11.

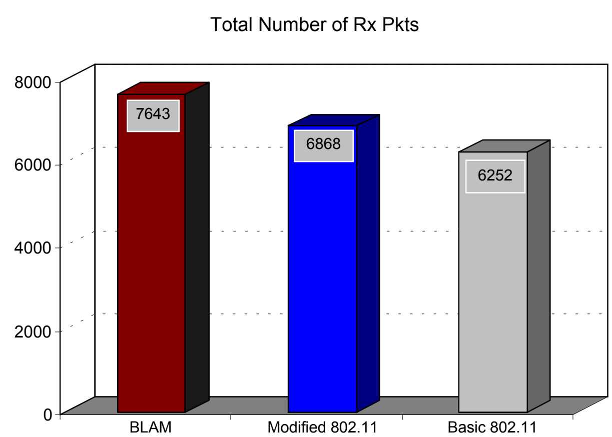


Fig. 18. Total Number of Received Packets with No Power Management

Because, BLAM decreased the network contention, more packets are delivered to their final destination and hence boost network throughput. As shown in Figure 18, BLAM increased the total number of received packets by 23% over the Basic 802.11 and by 12% over the Modified 802.11. A similar result is obtained for the total number of transmitted packets, depicted in Figure 19, decreasing the network contention reduced the number of retransmissions and the total number of data and control packets sent by BLAM is much less than the other two protocols.

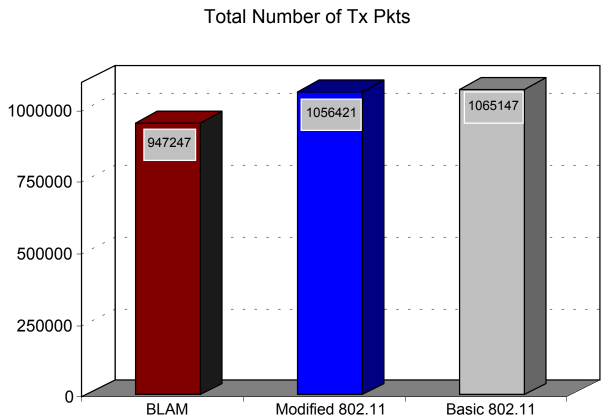


Fig. 19. Total Number of Transmitted Packets with No Power Management

VII. Conclusion

In our work we introduce BLAM, a new energy-efficient MAC layer protocol that is designed to extend the useful lifetime of a wireless adhoc network. We have shown that the IEEE 802.11 DCF protocol is not optimal in utilizing the scarce channel and energy capacities of the adhoc hosts. In a multihop adhoc network, a lot of energy and bandwidth are wasted due to collisions and retransmissions of control frames at each hop. Moreover, the contention between low-energy and high-energy nodes can deplete the critical nodes from their remaining energy and cause a partition in the network.

BLAM modifies both the probability of transmission for fresh data and the random deferring time in order to assign a priority to each node based on its residual energy. Consequently, nodes will be classified into virtual priority classes based on their energy. As a result, channel acquisition will be distributed among the different classes which decrease the number of collision and the contention for medium access will be only restricted to the members of a single class.

We validated the effectiveness of the proposed protocol through extensive simulations. For a medium loaded network, when comparing BLAM to the IEEE 802.11 DCF, BLAM successfully decreased the total number of collisions by almost 34% and was able to extend the lifetime of the network by 15% and the throughput by about 35%.

Furthermore, we have shown that BLAM is backward compatible with the currently deployed IEEE 802.11 MAC and does not require any special support at the routing layer or at the physical layer.

In the future the effect of BLAM on the routing layer protocol operation will be further studied. The consequences of changing the priority classes (for example, reversing the priorities) will be investigated on route requests and new route establishment. Moreover, based on the node priority class and the number of collisions faced, the MAC layer may set a time delay before sending a *Route-Reply* message to bypass energy-critical nodes.

References

[1] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination funtion," *IEEE Journal on Selected Areas in Communications, JSAC*, vol. 18, March 2000.

[2] F. Cali, M. Conti, and E. Gregori, "Dynamic tunning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Transactions on Networking*, vol. 8, pp. 785–799, December 2000.

[3] H. S. Chaya and S. Gupta, "Performance modeling of asynchronus data transfer methods of IEEE 802.11 mac protocol," *Wireless Networks*, pp. 217–234, 1997.

[4] J. Chen, K. Sivalingam, and P. Argawal, "Performance comparison of battery power consumption in wireless multiple access protocols," *ACM Wireless Networks*, vol. 5, no. 6, pp. 445–460, 1999.

[5] C. Chiasserini and R. Rao, "A distributed power management policy for wireless ad hoc networks," in *IEEE Wireless Communications and Networking Conference, WCNC*, 2000.

[6] B. P. Crow, I. Widjaja, J. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," *IEEE Communication Magazine*, pp. 116–126, 1997.

[7] J. Ebert, B. Stremmel, E. Wiederhold, and A. Wolisz, "An energy-efficient power control approach for WLANs," *IEEE Journal of Communications and Networks*, vol. 2, September 2000.

[8] J. P. Ebert, B. Burns, and A. Wolsi, "Measurment and simulation of the energy consumption of an WLAN interface," tech. rep., Technical University of Berlin, June 2002.

[9] J. P. Ebert, B. Burns, and A. Wolsiz, "A trace-based approach for determining the energy consumption of an WLAN network interface," in *European Wireless Conference*, pp. 230–236, February 2002.

[10] L. Feeney and M. Nilsson, "Investigating the energy consumptio of a wireless network interface in an adhoc networking environment," in *IEEE Infocom*, April 2001.

[11] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving transmission power in wireless ad hoc networks," in *IEEE International Conference on Network Protocols, ICNP*, November 2001.

[12] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian, "PARO: supporting dynamic power controlled routing in wireless ad-hoc networks," *Wireless Networks, WINET*, 2003.

[13] M. J. Handy, M. Haase, and D. Timmermann, "Low energy adaptive clustering hierarchy with deterministic cluster-head selection," in *IEEE International Conference on Mobile and Wireless Communications Networks, MWCN*, 2002.

[14] W. B. Heinzelman, *Application-Specific Protocol Architectures for Wireless Networks*. PhD thesis, MIT, 2000.

[15] "IEEE Std 802.11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications." IEEE Standards Board, 1997.

[16] D. B. Jhonson and D. A. Maltz, "Dynamic source routing in Ad Hoc wireless networks," *Mobile Cpmputing*, vol. 353, 1996.

[17] C. Jones, K. Sivalingam, P. Argawal, and J. Chen, "A survey of energy efficient network protocols for wireless networks," *Wireless Networks, WINET*, vol. 7, pp. 343–358, July 2001.

[18] S. McCanne, "Ns-2 (network simulator version 2)." URL: http://mash.cs.berkeley.edu/ns, 1997.

[19] S. Pattem, S. Poduri, and B. Krishnamachari, "Energy-quality tradeoffs for target tracking in wireless sensor networks," in *International Symposium on Aerospace/Defense sensing Simulation and Controls, Aerosense*, April 2003.

[20] C. Price, "Power-aware scheduling algorithms for wireless networks," in *MSc thesis, Washington State University*, 2001.

[21] M. Pursley, H. Russell, and J. Wysocarski, "Energy-efficient transmission and routing protocols for wireless multiple-hop networks and spread-spectrum radios," in *EUROCOMM 2000*, pp. 1–5, 2000.

[22] S. Singh and C. S. Raghavendra, "Power efficient mac protocol for multihop radio networks," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, 1998.

[23] K. Sivalingam, J. Chen, P. Argawal, and M. Srivastava, "Design and analysis of low-power access protocols for wireless and mobile atm networks," *ACM Wireless Networks*, vol. 6, no. 1, pp. 73–87, 2000.

[24] Y. Tay and K. C.Chuan, "A capacity analysis for the IEEE 802.11 MAC protocol," *ACM/Baltzer wireless Networks*, no. 2, pp. 159–171, 2001.

[25] C. Ware, T. Wysocki, and J. Chicharo, "On the hidden terminal jamming problem in IEEE 802.11 mobile ad hoc networks," in *IEEE International Conference on Communcations, ICC*, 2001.

[26] J. Weinmiller, M. Schlager, A. Festag, and A. Wolisz, "Performance study of access control in wireless LANs IEEE 802.11 DFWMAC and ETSI RES 10 HIPERLAN," *Mobile Networks and Applications*, pp. 55–67, 1997.

[27] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," in *International Conference on Mobile Computing and Networking, MobiCom*, 2001.