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

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***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 random deferring time for fresh and collided data packets based on the node's energy. We show that BLAM can achieve an increase of 15% in the 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 802.11 MAC protocol.*

I. INTRODUCTION

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 node's energy consumption. The nodes need to be energy conserving so that total time in which the network is connected and functioning is maximized.

This work builds upon our previous work [5] in which we observed that the IEEE 802.11 standard, when deployed in an adhoc network, can operate very far from optimality, and much channel bandwidth and energy are wasted in collisions and collision resolutions. This motivates us to propose a new energy-aware enhancement for the IEEE 802.11 to try to conserve both the nodes energy and the channel capacity wasted in collisions.

Toward this goal, we introduce a *Battery Level Aware MAC* (BLAM) which tunes the random deferring time for both fresh packets and collided ones based on the node's current relative battery level. As a result, BLAM reduces contention between low and high-energy nodes, saving the energy wasted in collision.

The rest of the paper is organized as follows: Section II reviews the IEEE 802.11 protocol. Section III presents related work. 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. Section VII discusses some shortcomings for BLAM. We conclude the paper in Section VIII.

II. OVERVIEW OF IEEE 802.11 DCF PROTOCOL

In the IEEE 802.11 DCF [10] medium access protocol, 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 sensing an idle channel for a so-called SIFS interval. The source transmits its data frame only if it receives the CTS correctly. If not, it is assumed that a collision occurred and an RTS retransmission is scheduled. After the data frame is received by the destination station, it sends back an acknowledgment frame.

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. Figure 1 illustrates the operation of the IEEE 802.11 DCF.

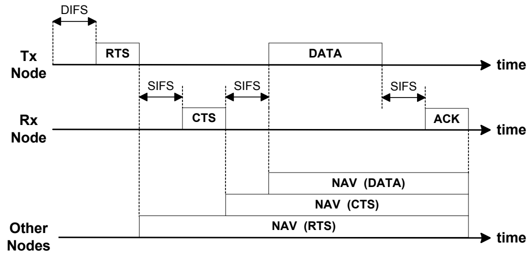

Fig. 1. IEEE 802.11 DCF Operation

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.

CW value depends on the number of failed transmissions of a frame. Figure 2 illustrates the increase of the contention window size using an exponential backoff mechanism.

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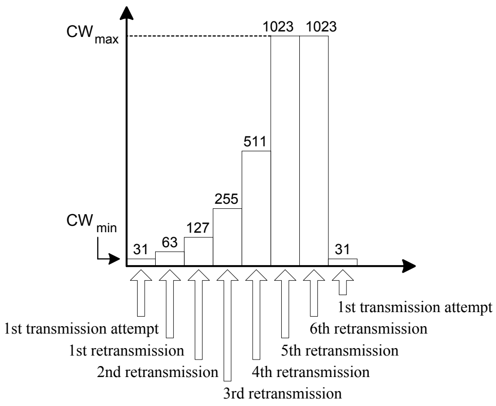


Fig. 2. Exponential Increase of the CW

III. RELATED WORK

Recognizing the challenge of energy consumption in adhoc networks, much research is directed toward the design of energy aware protocols. We can categorize the previous research on power-aware MAC layer into three categories:

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 [15] presented the idea of applying reservation schemes in wireless networks MAC protocols for energy conservation. EC-MAC's definition could be extended to adhoc networks, where a group of nodes may select some type of coordinator to perform the base station functions, as proposed in [1] and [12]. Furthermore, because the coordinator's role consumes the resources of certain nodes, a group of schemes were proposed in which coordinators are rotated among network nodes [8] [9].

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 [14], allows a station to power its radio off but has to keep a separate channel on which the RTS/CTS packets are received. Similarly, Chiasserini [2] allows a station to go to sleep, but a special hardware is required to receive wakeup signals. Also, in [17] the geographical area is partitioned into smaller grids in each of which only one host needs to remain active to relay packets.

c) Transmission Power Control: came about because the maximum power is consumed during the transmission mode. According to the path-loss radio propagation model there is a non-linear relation between the transmission power and the transmission distance. It is more energy conserving (considering only transmission energy) to send the data in a multi-hop fashion using relay nodes rather than sending it directly to the destination. PARO [7], for example, favors forwarding the data to the nearest neighbor until reaching the destination.

A simple power control scheme for the 802.11 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 introduce asymmetric links, a problem known as the "Hidden Terminal Jamming" problem [16]. 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, 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 [6] [13].

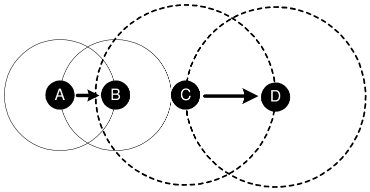


Fig. 3. Hidden Terminal Jamming Problem

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 [13] 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 the 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, therefore, based on that observation, the protocol in [3] 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. The higher the number of collisions the lower the network throughput is and the higher energy is consumed resolving them.

The situation might be worse in a multihop wireless adhoc network, because each message potentially encounters collisions at each hop. As a result, the total number of collisions increases and more channel bandwidth and energy are wasted [5].

The multihop effect is augmented in power-aware adhoc networks because the basic power control scheme favors transmitting the data to the nearest neighbor instead of transmitting it to a further one. Accordingly, the power-aware route will be composed of a big number of shorter hops causing the number of collisions 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 [6] [13]. However, the drawback of this scheme 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. 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 energy. **All the modifications** that BLAM add to the MAC operations **are totally localized** and thus BLAM is **backward compatible** with the IEEE 802.11 protocol.

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 high-energy nodes. 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 located in the confluence of many routes. Leaving these critical nodes to deplete their energy may cause a network *partition* and some sources might be unable to reach other destinations. BLAM proposes a new philosophy so that the nodes are probabilistically 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.

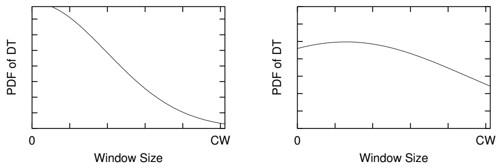
B. Modifications to IEEE 802.11 DCF

BLAM modifies the IEEE 802.11 DCF in two ways, changing the wait time before transmitting 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, it first senses the medium, if found idle for a DIFS interval, it immediately sends an RTS. In contrast, in BLAM, after sensing an idle channel for a DIFS interval, the node waits for a random amount of time before sending the RTS (if the medium is found idle). This random wait time is picked from a normal distribution with mean and variance that depend on the current node's battery level:

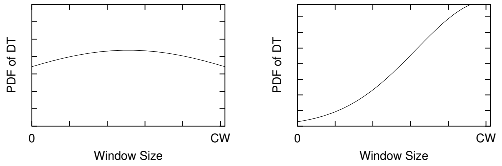
$$\begin{aligned} Mean &= CW_{min}\cdot(1-R_i) \\ Variance &= \frac{CW_{min}}{2}\cdot cosine\left(2\cdot\left|\frac{1}{2}-R_i\right|\right) \end{aligned} \tag{1}$$

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

Furthermore, in IEEE 802.11, 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 contention window size. In BLAM, the random deferring period is picked up from a *normal* distribution with the mean and variance are as given by Equation 1, replacing CW_{min} with the current contention window size CW. As in 802.11, the value of CW will double at each unsuccessful transmission.



(a) Battery level = 1 (b) Battery level = 0.75



(c) Battery level = 0.5 (d) Battery level = 0

Fig. 4. Deferring Time Distribution with a Variable Mean and Variance

Figure 4 depicts the normal distribution from which the deferring time is determined at four representative battery levels, ranging from full to empty capacities.

When a node has full battery, the distribution of the random deferring time will be as shown in Figure 4(a). As a result, it is most probable that a high-energy node will pick a short deferring time. This 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 right, as shown in Figures 4(b), 4(c) and 4(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 4(d), and thus these nodes will probably pick longer deferring time and will have less chance to access the medium and a low priority.

The idea is the same for fresh data transmission probability. Consequently, the transmission probability of fresh data will be higher in the high-energy nodes (higher priority) and will decrease as the node consumes its battery.

In that manner, the network nodes are divided among a *continuous* set of priorities based solely on *local* information, that is, based on their energy levels. Each node will eventually get its share to access the channel based on its assigned priority. Therefore, the 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, for the nodes that have low or high energy, the variance of the distribution is smaller than that defined at the mid-range battery levels. 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 would force 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 4(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, therefore, further contention between low-energy and high-energy nodes is restricted. Consequently, low-energy nodes will not waste their scarce energy colliding with high-energy nodes and thus, the useful network lifetime is extended.

C. Low-Energy Nodes Priority

One objection for BLAM may arise because of the low priority assigned to the energy-poor nodes. It might seem more reasonable to give low-energy nodes a higher priority to access the channel so that they send their data immediately before they die. However, the unfairness to these nodes is intentional and is designed in such a way to further extend the network lifetime.

First, in BLAM, a high-energy node will be transmitting more often, consequently, it will have a battery consumption rate higher than that of the low-energy nodes. This means that BLAM is balancing the residual energy level among the whole network nodes and accordingly, it is delaying the network partition event as much as possible.

Second, as shown in Section VI, BLAM has a lower average end-to-end delay per packet (compared to IEEE 802.11) because it eliminated the time wasted in collision detection/resolution and in retransmissions. This indicates that *on average* the energy-poor nodes are not waiting longer than usual before getting their chance to transmit their data, therefore, these nodes are in fact not facing any starvation.

Finally, we believe that during new route discovery, because the energy-poor nodes have a lower chance to access the channel, they will have smaller probability to participate in new forwarding routes. The routing layer will *transparently* bypass the routes that pass through these critical nodes and choose routes that might have a longer delay but will last longer and thus extend the network lifetime.

This idea is depicted in Figure 5, where the high energy node (*Node 3*) was selected to participate as a forwarding node, which conserves the energy of the other two critical nodes. Accordingly, the scarce energy of the critical nodes will not be used in new forwarding routes but rather in transmitting the nodes' own data (and the forwarded data for the routes the node is already member in).

D. Discussion

The effectiveness of BLAM is due to our design: *All the modification are localized*, that is, the modifications are based on the local host information and are only implemented within the wireless node itself.

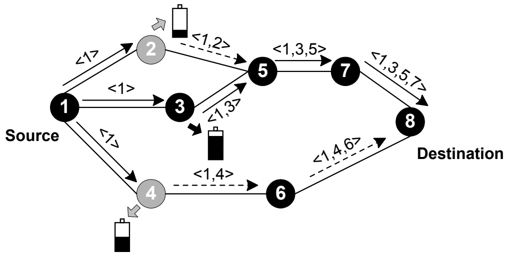


Fig. 5. Route Request Propagation

Accordingly, BLAM 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. Also, it does not require any specific support from the routing layer above or from the physical layer beneath. That is, BLAM is *backward compatible* with a network that uses the IEEE 802.11 MAC protocol and also it can be easily incorporated in this widely used protocol. The required modifications can be implemented as a simple 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 random deferring time before transmission.

Moreover, 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 neighbors (to poll the nodes' status), as these *Request-Status* messages and their replies might increase the network load and waste both the channel bandwidth and the hosts' energy.

V. ENERGY MODEL AND SIMULATION ENVIRONMENT

In our simulation analysis 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 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 [4] (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)

We used the *Network Simulator* (NS2) to simulate BLAM. We have done an intensive simulation analysis of BLAM covering different network loads, different total number of nodes, different routing protocols and different transport layer protocols. BLAM shows improvement over the IEEE 802.11 DCF protocol in most of these simulation scenarios.

Due to space limitations, we are only presenting a subset of these simulation results in which a network that covers an area of $1000 \times 1000\, m^2$, with 60 nodes randomly distributed in this area is simulated. A total number of 50 flows are generated, each flow is assumed to be a constant bit rate (CBR) flow. Each flow has the rate of 2 packets/source/sec and the packet size is 512 bytes.

For each flow the source and the destination are randomly chosen. Dynamic Source Routing (DSR) [11] is used. It should be noted that the basic DSR protocol minimizes the number of hops between the source and destination. BLAM will do better if another power-aware routing protocol (one that minimizes transmission distance between hops) is used because in that case (see Section IV) the percentage of energy wasted in collision will be higher.

Initially, all the nodes are assumed to have full battery level of 5 joules; battery capacity was set to a small value to scale down the simulation time. It should be mentioned that BLAM savings would be higher if the network nodes were having heterogeneous battery levels at the start of the simulation. This is because the nodes will be assigned different priorities which will cause the number of collisions to decrease even more. 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. Simulation parameters are summarized in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of Simulation runs	10
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

We compare BLAM with two versions 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.

Figure 6 compares the total number of RTS/CTS frame collisions in the network for the period of the network lifetime (i.e., until the first node dies) when the basic power management protocol is used. As shown in Figure 6, BLAM successfully decreased the total number of collisions by 36% over the Basic 802.11 and by 31% over the Modified 802.11.

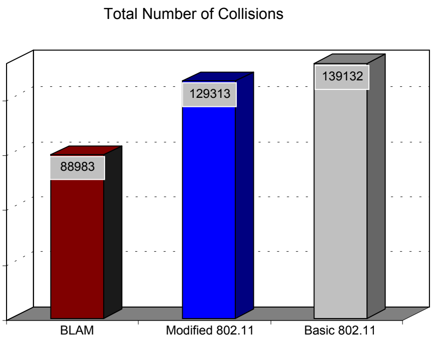
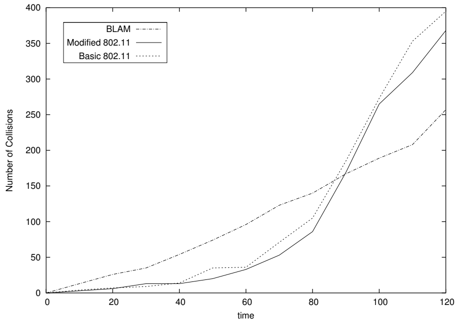
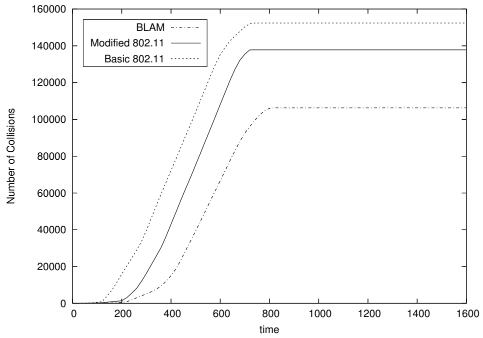


Fig. 6. Total Number of Collisions



(a) Detailed interval (0-120) seconds



(b) Overall behavior

Fig. 7. Number of Collisions versus Time

Figure 7 represents the accumulated number of collisions over time. At the beginning, all the nodes will have a full battery and the distribution presented in Figure 4 will have a small variance. Therefore, the nodes will pickup comparable values 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 (as shown in Figure 7(a)). 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. 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 since the window is smaller for nodes with low battery level. However, this effect is insignificant because it occurs when almost all the routes in the network are broken and no packets can be transmitted.

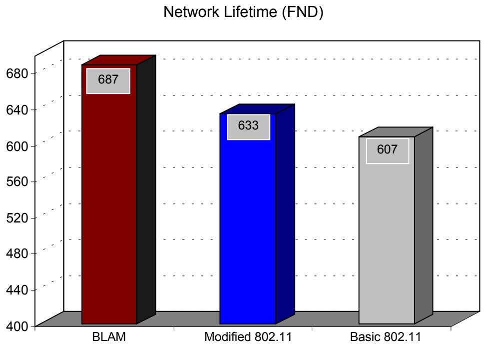


Fig. 8. Network Lifetime (in seconds)

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. Moreover, 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. We define the network lifetime as the time duration from the beginning of the simulation until the instant when the First Node Dies (FND). As shown in Figure 8, the lifetime for BLAM is 15% more than that of the Basic 802.11 and 9% more than the Modified 802.11.

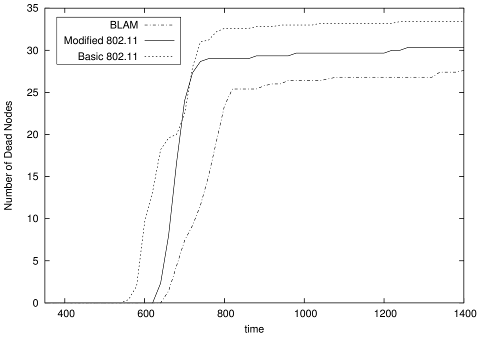


Fig. 9. Number of Dead Nodes versus Time

Figure 9 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. 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.

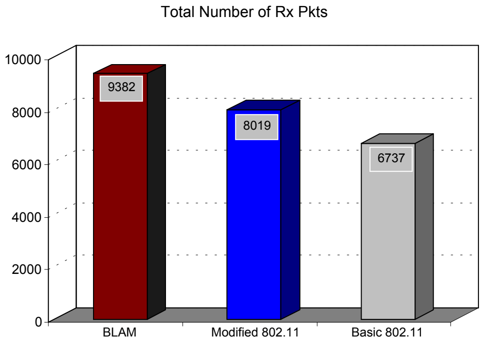


Fig. 10. Total Number of Received Packets

Decreasing the number of collisions and increasing the network lifetime could be easily achieved by forcing the nodes to send less data. However, this scheme would have the drawback of decreasing the network utilization and decreasing the total number of received packets. BLAM, however, does not force the network nodes to send less data but rather forces them to decrease the number of retransmitted control frames (which saves energy and extends network lifetime). As a result more data packets are able to reach their final destination. Figure 10 compares the total number of data packets that are correctly received by the destination application in the three MAC protocols. As shown in Figure 10, BLAM increased the total number of received data packets by 39% over the Basic 802.11 and by 16% over the Modified 802.11.

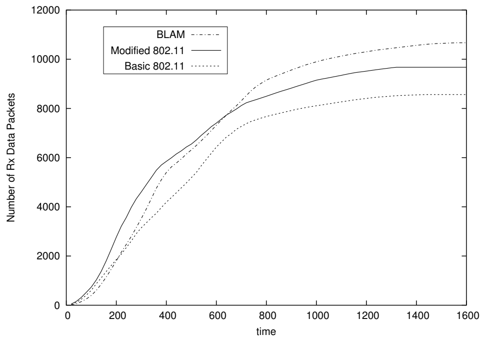


Fig. 11. Number of Received Packets versus Time

Figure 11 shows the accumulated number of the correctly received data packets versus time. At the start of the simulation, as discussed before, the number of collisions faced when using BLAM will be higher than the other protocols. As a result, BLAM will deliver less data packets to their final destination as indicated in Figure 11. However, as time goes by, transmitting nodes will consume their energy and move towards another priority (no contention), thus, the number of collisions decrease and more packets will be correctly received.

The network throughput is defined as the total number of received packet divided by the time. Consequently, the throughput can be seen as the slope of the curve shown in Figure 11. Towards the end of the simulation the curve in

Figure 11 flattens which indicates that the throughput of the network is close to zero and hence no more messages are being received. This is because most of the network nodes are dead and no data packets can make through to their destinations.

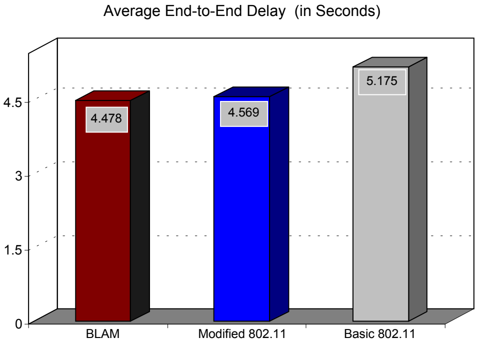


Fig. 12. Average End to End Delay Per Packet

Figure 12 shows the comparison between the average end-to-end delay faced by a packet in the three MAC protocols. As shown in Figure 12, BLAM has a lower end-to-end delay than both the Basic 802.11 and the Modified 802.11. This surprising result is because of the fact that, although the low-energy nodes are deferring longer before transmission, the time is not wasted in collisions detection/resolution and in retransmissions. It should also be noted that BLAM, similar to the IEEE 802.11 DCF MAC protocol, does not offer an upper bound on the delay actually faced by a node before successfully transmitting its data packet.

VII. SHORTCOMINGS AND FUTURE WORK

Although BLAM shows much better performance than the IEEE 802.11, it still has some shortcomings. First, because of BLAM's simplicity and backward compatibility, it determines the waiting time before transmission based *only* on the node energy. Better performance improvement is achievable if we let the higher protocol layers convey more information to BLAM. For example, number of neighbors, remaining hops to destination, application QoS requirements can all be used to determine waiting time before transmission at the MAC level.

Second, when the all network nodes have either full battery level (in the beginning) or low battery level (at the end) BLAM will introduce more collisions and hence more energy is wasted. BLAM will only show improvement over the IEEE 802.11 when the nodes have heterogeneous remaining energy (this will eventually occur because some nodes will transmit more than the others). However, the above cases are avoidable if a node knows the battery levels of all its neighbors. This can be implemented by adding a field to the RTS in which the node reports its current remaining energy although this would harm the backward compatibility.

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.

VIII. CONCLUSION

In our work we introduced BLAM, a new energy-efficient MAC layer protocol that is designed to extend the useful lifetime of a wireless adhoc network.

BLAM modifies the waiting time before fresh data transmission and the deferring time after a collision in order to assign a priority to each node based on its residual energy. Furthermore, we designed BLAM to be backward compatible with the currently deployed IEEE 802.11 MAC.

We validated the effectiveness of the proposed protocol through simulations. When compared 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%.

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