Modeling an Energy-Efficient MAC Layer Protocol

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***Abstract*— *In wireless adhoc networks, channel and energy capacities are scarce resources. In our previous work we proposed BLAM, a new energy aware MAC layer enhancement for the IEEE 802.11 protocol to save the energy and channel capacity wasted in collisions. In this paper we introduce a collision model to analytically compare BLAM to the IEEE 802.11. Using this model we provide worst-case and best-case analysis for BLAM's behavior. We verified the correctness of the model using simulation analysis. Furthermore, for real network traffic, we show that in a WLAN BLAM can achieve an 8% increase in the network lifetime and an increase of about 40% in the total number of received packets. This paper complements the previous results obtained for a mutihop adhoc network.*

I. Introduction

Adhoc networks have witnessed an explosion of interest in the last few years as they are expected to have significant impact on the efficiency of many military and civilian applications. However, one of the constraints for building efficient adhoc networks is *finite* battery supply. Usually the network nodes are battery operated and in many cases they are installed in an environment where it may be hard (or undesirable) to retrieve the nodes to change or recharge the batteries. It is crucial to design techniques to reduce the network energy consumption so that the total time in which the network is connected and functioning is maximized.

In our previous work [5] 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 motivated us to propose a new energy-aware MAC layer enhancement for the IEEE 802.11. We proposed a *Battery Level Aware MAC* (BLAM) [6, 7] 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 both the nodes energy and the channel capacity wasted in collision. We showed that, in a multihop adhoc network, BLAM can achieve an increase of 15% in the network lifetime and an increase of 35% in the total number of received packets.

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In this paper, we use the analytical collision model that we introduced in our previous work [5] to compare the probability of collision in both BLAM and the IEEE 802.11 protocols. Using this model we prove that the worst-case probability of collision in BLAM is only 13% higher than that of IEEE 802.11, while in the best case BLAM reduced the probability of collision by almost 4 folds. We verified the correctness of the proposed model using simulation analysis. Furthermore, for a single-hop network with 60 flows of CBR traffic, we show that BLAM when compared to IEEE 802.11 can achieve an 8% increase in the network lifetime and an increase of about 40% in the total number of received packets with a 50% reduction in the total number of collisions. This indicates that, in a real network traffic, the worst case of BLAM is not frequent.

The rest of the paper is organized as follows: Section II reviews the IEEE 802.11 protocol. Section III presents related work. Sections IV reviews the BLAM protocol operations. Section V describes the collision model used and verifies its correctness. Simulation results are presented in Section VI. We conclude the paper in Section VII.

II. Overview of IEEE 802.11 DCF Protocol

In the IEEE 802.11 DCF [13] 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.

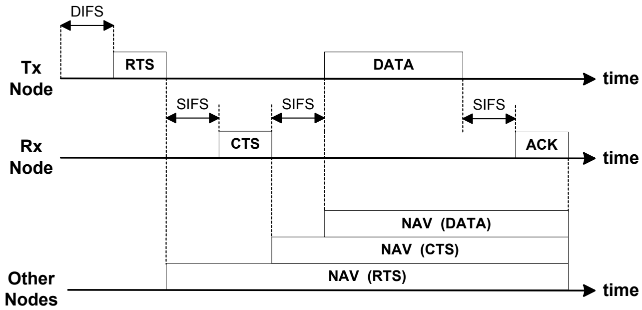


Fig. 1. IEEE 802.11 DCF Operation

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.

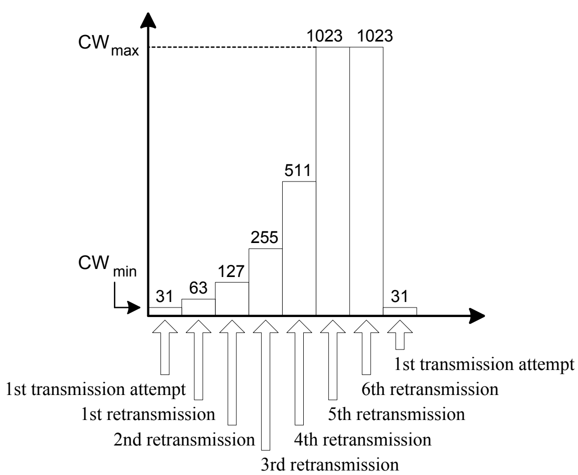


Fig. 2. Exponential Increase of the CW

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.

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) 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 [19], 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 [2] and [16]. 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. In [11] the coordinators are randomly chosen while in [10] the remaining battery capacity controls the probability of coordinator selection.

b) Switching off Power-Aware MAC: tries to minimize the idle energy consumption by forcing nodes to enter the *doze* mode. For example, PAMAS [18], 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 [3] allows a station to go to sleep, but a special hardware is required to receive wakeup signals. Also, in [22] the geographical area is partitioned into smaller grids in each of which only one host needs to remain active to relay packets. Furthermore, Pattem [15], discussed various activation strategies for the nodes, including Randomized, Selected and Duty-cycle modes.

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 [9], for example, favors forwarding the data to the nearest neighbor until reaching the destination.

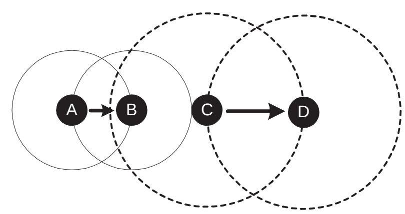


Fig. 3. Hidden Terminal Jamming Problem

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 [21]. 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 shown 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 [8] [17].

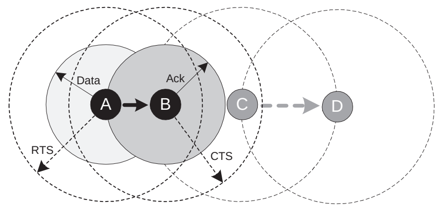


Fig. 4. Control Frames with Maximum Power

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 [17] adjusts the transmission power according to the signal-to-noise ratio 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 [4] chooses an appropriate transmission power based on the packet size.

IV. Battery Level Aware MAC (BLAM)

A. Motivation

In wireless LANs, the nodes included in the coverage area of a certain host may send control messages that collide with the RTS/CTS frames transmitted by this host. 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. 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 [5]. Furthermore, as mentioned in Section III, a smarter power aware scheme will transmit the short control frames using a higher power than the data frames [8] [17]. 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 energy by decreasing the total number of collisions.

Furthermore, in IEEE 802.11, 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. 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 packet arrives at a node, it first senses the medium, and 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. This random wait time is picked from a normal distribution with mean and variance that depend on the current node's battery level:

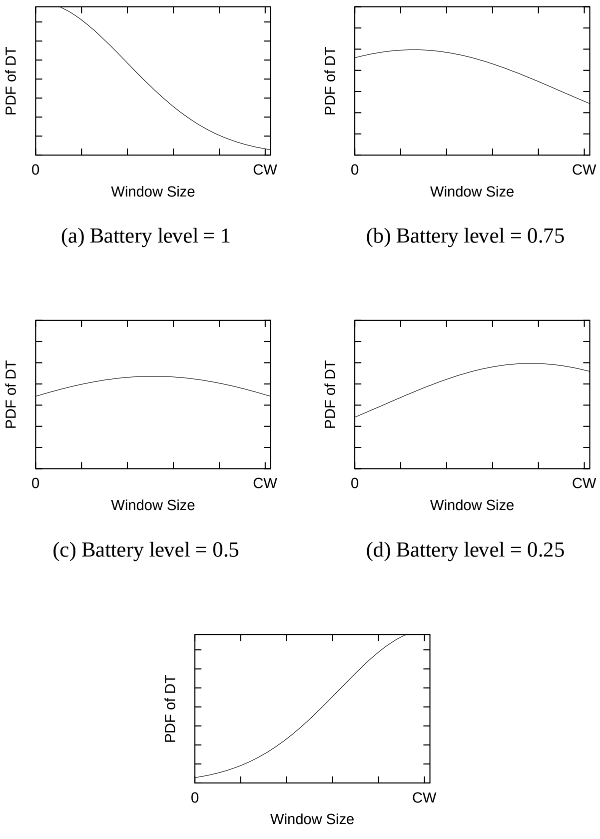
$$\begin{aligned} Mean &= CW_{min} \cdot (1 - R_i) \\ Variance &= \frac{CW_{min}}{2} \cdot cosine\left(2 \cdot \left|\frac{1}{2} - R_i\right|\right) \end{aligned} \tag{1}$$

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 given by Equation 1, replacing CW_{min} with the current contention window size CW.

Figure 5 depicts the normal distribution from which the deferring time is determined at five 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 5(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 5(b), 5(c), 5(d) and 5(e), 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 5(e), and thus these nodes will probably pick longer deferring time and will have less chance to access the medium



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

(c) Battery level = 0.5 (d) Battery level = 0.25

(e) Battery level = 0

Fig. 5. Deferring Time Distribution with a Variable Mean and Variance

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. Additionally, low-energy nodes will not waste their scarce energy colliding with high-energy nodes and thus, the useful network lifetime is extended.

It should be noted that all the modifications that BLAM introduces to the MAC protocol operations are based on the local host information and are only implemented within the wireless node itself. 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 can be easily incorporated in this widely used protocol.

V. Collision Analysis

A. *Collision model*

In our previous work [5] we proposed a collision model for the IEEE 802.11. In this paper, we apply the same model to the BLAM protocol and use the results to compare the worst-case and best-case behavior of BLAM and the IEEE 802.11 DCF protocol.

In our network model, we assume that a set of homogeneous adhoc nodes are uniformly distributed over a two dimensional area with node density given by ρ per unit area. Each node can communicate directly with all the nodes within its coverage area, where the coverage area of the node is defined by the radius which the control frames can reach (defined as a_{RTS}). We assume that the smart power control scheme, as mentioned in Section III, is used. The distance between the sender and the receiver is given by a_{data}. Furthermore, we will assume that the time is slotted with slot time τ. We define the *number of time slots* needed to send an RTS packet as L_{RTS} slots. Analogously, The number of time slots needed to send a CTS, a data packet, and an acknowledgment packets are L_{CTS}, L_{data}, and L_{ack}, respectively.

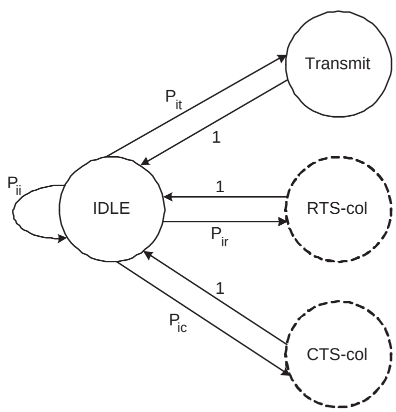


Fig. 6. Wireless Channel State Transition Diagram

The wireless channel state transition diagram around a certain node x is shown in Figure 6. *IDLE* is the state when channel around node x is sensed idle, and its duration is for one time slot, τ. The *Transmit* state indicates that a successful four-way handshake is completed, and hence, its duration is $T_{transmit} = L_{RTS} + L_{CTS} + L_{data} + L_{ack}$. The *RTS-col* state indicates that multiple hosts within the coverage area of node x transmit RTS frames concurrently, causing an RTS collision; its duration is $T_r = L_{RTS}$. Finally, the *CTS-col* state indicates that a terminal hidden from node

x sends some packets that collide at the receiver with the RTS being received or the CTS being sent; its duration is $T_c = L_{RTS} + L_{CTS}$.

In our analysis, we assume that the nodes are fully saturated, that is, always having a packet waiting in the output buffer to be sent. The probability that a node transmits at a given time slot is given by p. In Section V-B we will evaluate p for both BLAM and the IEEE 802.11.

The probability P_{ii} is the transition probability from *IDLE* to *IDLE*, that is, the probability that none of the nodes within the coverage area of x transmits at this time slot. P_{ii} is given by:

$$P_{ii} = (1-p)^M \tag{2}$$

where $M = \rho \cdot \pi a_{RTS}^2$ is the total number of nodes included in the coverage area of node x.

The probability P_{it} is the transition probability from *IDLE* to *Transmit*. It is the probability that exactly one node transmits at this time slot and starts a successful four-way handshake (i.e., other nodes withhold their transmission). P_{it} is given by:

$$P_{it} = M \cdot \Pi_s \cdot (1-p)^{M-1} \tag{3}$$

where Π_s denotes the probability that a node begins a successful four-way handshake at this time slot. Π_s is a function of the number of hidden terminals and the distance between the sender and the receiver as will be discussed later.

The probability P_{ir} is the transition probability from *IDLE* to *RTS-col*, that is, the probability that two or more nodes transmit an RTS packet at the same time slot. In other words, P_{ir} is (1 − *probability that none of the nodes transmits* − *probability that exactly one node transmits*):

$$P_{ir} = 1 - (1-p)^M - M \cdot p \cdot (1-p)^{M-1} \tag{4}$$

Finally, P_{ic}, the transition probability from *IDLE* to *CTS-col*, can be simply computed as:

$$P_{ic} = 1 - P_{ii} - P_{it} - P_{ir} \tag{5}$$

Having calculated P_{ii}, P_{it}, P_{ir} and P_{ic}, the equilibrium equations of the wireless channel state transition diagram can be deduced and solved, so that the *Transmit* state limiting probability, θ_t, can be computed. θ_t represents the percentage of time in which the node is successfully transmitting, or in other words, it is the ratio between successful transmission time to the total network time (defined as the summation of transmission time and contention time). The solution of the state model equilibrium equations is:

$$\theta_t = \frac{P_{it}}{1 + P_{it} \cdot T_{transmit} + P_{ir} \cdot T_r + P_{ic} \cdot T_c} \tag{6}$$

All the terms of Equation (6) have been derived with the exception of P_{it} as it depends on Π_s, the probability that a node starts a successful four-way handshake in the given time slot. In order to determine, Π_s, the state transition diagram of a wireless node is constructed as shown in Figure 7. Node x is in the *succeed* state when it can complete a successful four-handshake with the other nodes, and it enters the *fail* state when the node initiates an unsuccessful handshake. On the other hand, the *wait* state accounts for deferring for other nodes. Π_s is the limiting probability of the *succeed* state, as computed next.

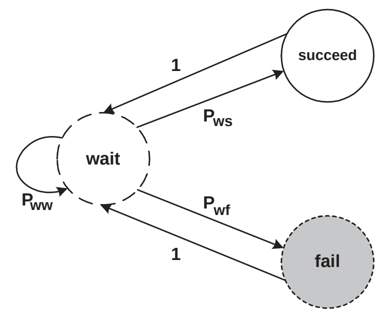


Fig. 7. Wireless Node State Transition Diagram

We define $B(a_{data})$ to be the hidden area from node x when communicating with node R located at a_{data} away from it, as illustrated in Figure 8. Takagi [20] has proved that $B(a_{data})$ takes the form:

$$B(a_{data}) = \pi \cdot a_{RTS}^2 - 2 \cdot a_{RTS}^2 \cdot \{arccos(\frac{a_{data}}{2 \cdot a_{RTS}}) - \frac{a_{data}}{2 \cdot a_{RTS}} \cdot \sqrt{1 - \frac{a_{data}^2}{4 \cdot a_{RTS}^2}}\} \tag{7}$$

The number of nodes hidden from the sender, computed as $\rho\, B(a_{data})$, are not included in the sender coverage area but are within the receiver node coverage *and* can collide with the RTS frame being received or the CTS frame transmitted by the receiver.

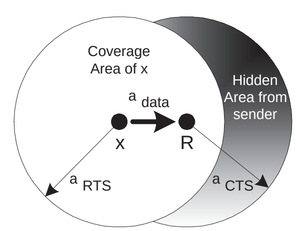


Fig. 8. Hidden Area From the Sender

The transition probability P_{ww}, from *wait* state to *wait* state, is the probability that neither node x nor any node within its coverage area is initiating any transmissions. P_{ww} is given by:

$$P_{ww} = (1-p)^M \tag{8}$$

The transition probability, P_{ws}, from *wait* state to *succeed* state is the probability that node x transmits at this time slot and none of the terminals within a_{RTS} of it transmits in the same slot, and also that none of the hidden nodes in $B(a_{data})$ transmits for $(L_{RTS}+L_{CTS})$ slots. P_{ws} can be written as:

$$P_{ws} = p\cdot(1-p)^M \cdot [(1-p)^{\rho\cdot B(a_{data})}]^{L_{RTS}+L_{CTS}} \qquad (9)$$

Finally, the transition probability P_{wf}, from *wait* state to *fail* state can be simply calculated as:

$$P_{wf} = 1 - P_{ww} - P_{ws} \qquad (10)$$

Solving the equilibrium equations of the wireless node state transition diagram, the limiting probability of state *succeed*, Π_s can be given by:

$$\begin{aligned}\Pi_s &= \frac{P_{ws}}{2-P_{ww}} \\ &= \frac{p\cdot(1-p)^M\cdot[(1-p)^{\rho\cdot B(a_{data})}]^{L_{RTS}+L_{CTS}}}{2-(1-p)^M}\end{aligned} \qquad (11)$$

The value of Π_s is substituted into Equation (3). Then the obtained value of P_{it} is substituted back into Equation (6) so that θ_t, the ratio between successful transmission time to the total network time, can be derived.

B. Probability of transmission

The difference between BLAM and the IEEE 802.11 lies in the probability of transmission, p. However, the probability of transmission differs for each time slot. We denote the probability of transmission in a given time slot i as $p(i)$. $p(i)$ in the BLAM case depends on the node's current energy level and the number of retries, while $p(i)$ in the 802.11 case only depends on the number of retries. To distinguish between the two protocols, we call $p(i)$ in the BLAM case $p_{blam}(i)$ while in the 802.11 case we call it $p_{802.11}(i)$.

In our analysis, as an approximation, we assume that the size of the *Contention Window* (CW) is held constant. Consequently, (As proved in [1] and [12]) the probability of transmission in a given time slot for the IEEE 802.11, $p_{802.11}(i)$, is constant and is given by

$$p_{802.11}(i) = \frac{2}{CW+1} \qquad (12)$$

On the other hand, In BLAM, using the same approximation, the probability of transmission in a given time slot, $p_{blam}(i)$, depends only on the energy distribution among the wireless hosts.

For a given node X, with relative energy level R_X (normalized to full energy), the probability that Node X transmits during slot i, $p_{blam}(i,R_X)$ can be computed as given by Equation 13 (and as depicted in Figure 9):

$$p_{blam}(i,R_X) = \int_{i-1}^{i} p_{BLAM}(t,R_X)\,dt \qquad (13)$$

where $p_{BLAM}(t,R_X)$ is the Probability Distribution Function (PDF) of transmission for Node X versus time at the fixed relative energy level R_X when using the BLAM protocol.

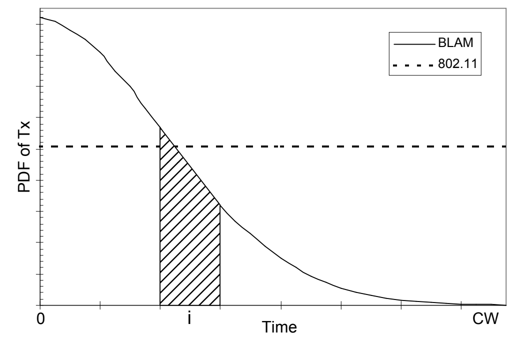


Fig. 9. Transmission Probability PDF for Node X with a Relative Energy Level R_X versus Time. ($p_{blam}(i,R_X)$ is the shaded area)

As a generalization for the previous case, for any neighborhood with a given distribution of energies among M wireless nodes (a snapshot of the network), $p_{blam}(i)$ can be defined as the average of the probabilities of transmission per node during this slot i. Hence, $p_{blam}(i)$ can be computed as

$$p_{blam}(i) = \frac{1}{M}\cdot\sum_{\Upsilon=R_1}^{R_M} p_{BLAM}(i,\Upsilon) \qquad (14)$$

where R_j is the relative energy level of Node j.

Equations 12 and 14 represent the probability of transmission in slot i for the IEEE 802.11 DCF protocol and for the BLAM protocol respectively. Using these equations the different transition probabilities of the collision model (see Section V-A) can be computed. In Section V-C we compare the probability of collision and the throughput in BLAM versus the IEEE 802.11. The results are presented in two cases, the worst case for BLAM, when all the M nodes are having equal full energy (i.e. $R_i = R_j = 1\ \forall i, j \in [1..M]$), and the best case for BLAM, when the neighborhood is having uniform distribution of the energies among the M nodes (i.e. $R_i = \frac{i}{M}\ \forall i \in [1..M]$).

C. Model results and verification

Using the analytical equations previously derived and substituting the different network parameters by the values shown in Table I, we present results for the comparison of average collision probability and average network throughput between BLAM and the IEEE 802.11.

To verify the correctness of the collision model, we also simulated a single-hop network using the Network Simulator (NS2) [14]. The maximum coverage area of a single node is of radius 250 m. The total area is set to 1.5 the coverage area of a single node to introduce hidden terminals. 16 nodes are uniformly distributed in each neighborhood. The

TABLE I

NETWORK PARAMETERS

Parameter	Symbol	Value
RTS packet time	L_{RTS}	13 *slot time*
CTS packet time	L_{CTS}	12 *slot time*
Data packet time	L_{data}	287 *slot time*
Ack packet time	L_{ack}	12 *slot time*
Contention window	CW	256 *slot time*
Nodes per neighborhood	M	16 *nodes*

network load was set to a high value to force the nodes' send buffer to be always full. Two sets of scenarios are simulated, in the first, all the nodes have full energy, while in the second, the nodes have uniform distribution of the remaining battery energy. The energy distribution is forced to be fixed from the start to the end of the simulation by assuming that transmitting, receiving and listening consume no energy.

The average collision probability can be computed as:

$$P_{collision} = \sum_i (p_{col}(i) \cdot p(i)) \tag{15}$$

where $p_{col}(i)$ is the probability of collision in slot i, defined as the summation of P_{ir} and P_{ic} in this slot time. While $p(i)$ is the transmission probability in slot i, as defined in Equations 12 and 14.

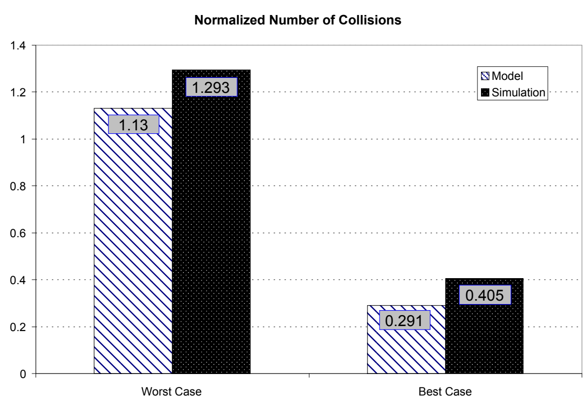


Fig. 10. Comparison of the Number of Collisions

Figure 10 compares the total number of collisions in the network in both the worst-case and the best-case for BLAM normalized to the number of collision faced when using the IEEE 802.11. As shown in Figure 10, in the worst-case, when all the nodes are having full energy, the number of collisions in BLAM is higher than that of the IEEE 802.11. Analytically, the probability of collision is higher by only 13%. Using the simulation, the number of collisions is higher by 29.3%. On the other hand, when the nodes are having uniform distribution of the remaining energy, the best case for BLAM, analytically, the probability of collision in BLAM is 29.1% that of the IEEE 802.11. Using the simulation analysis, the best-case of BLAM decreased the total number of collisions to 40.5% of its value. It should be mentioned that, the difference between the analytical and the simulation results is mainly because the collision model assumes a fixed mid-range contention window size (256 *slot time*) while in the simulations the CW lies in the range $[31..1023]$ *slot time* (as mentioned in Section II).

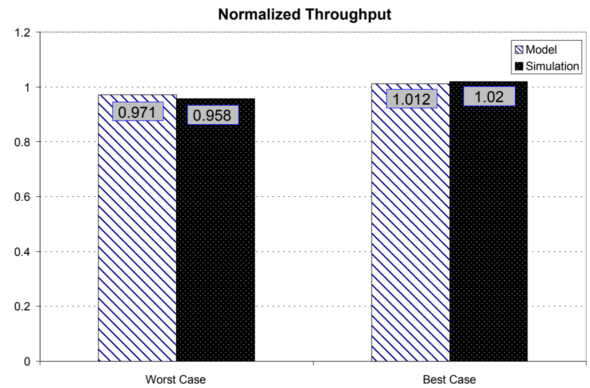


Fig. 11. Comparison of the Network Throughput

As proven in [5], the total network throughput is proportional to the percentage of time in which the node is successfully transmitting, θ_t. Figure 11 compares the analytical and simulation results for the ratio of the average throughput between BLAM and the IEEE 802.11. The results are presented both in the worst-case for BLAM, when all the nodes are having full energy, and in the best-case for BLAM, when the nodes are having uniform distribution of the remaining energy. As shown in Figure 11, when BLAM is used the total network throughput is almost equal to the network throughput offered by the IEEE 802.11. However, it should be noted that, BLAM extends the total network lifetime (as shown in Section VI), as a result, the network lives longer and hence, the total number of correctly received packets (network utility) is increased.

VI. SIMULATION RESULTS

In Section V-C simulation analysis is presented to verify the correctness of the proposed collision model, where a single-hop network with fixed-energy fully-saturated uniform-distributed wireless hosts are simulated. In this section we present simulation results for a real network scenario.

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, and 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.

We used the *Network Simulator* (NS2) [14] to simulate a single-hop network that covers an area of $375 \times 375\, m^2$, with 32 nodes randomly distributed in this area. A total number of 60 flows are generated, each flow is assumed to be a constant bit rate (CBR) flow. Each flow has the rate of 6 packets/source/sec and the packet size is 512 bytes. For each flow the source and a single-hop-away destination are randomly chosen.

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 (250 m). The receive power is assumed to be approximately 45% of the maximum transmit power. 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. 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 II.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of Simulation runs	10
Network Size	$375 \times 375\ m^2$
Node range	250 m
Node initial energy	5.0 J
Number of connections	60
Packet Size	512 bytes
Transmission rate per source	6 pkts/sec
Simulation time	1600 sec

Figure 12 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). As shown in Figure 12, BLAM successfully decreased the total number of collisions by 40% over the Basic 802.11 and by 31% over the Modified 802.11.

At the beginning, all the nodes will have a full battery and the distribution presented in Figure 5 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. 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

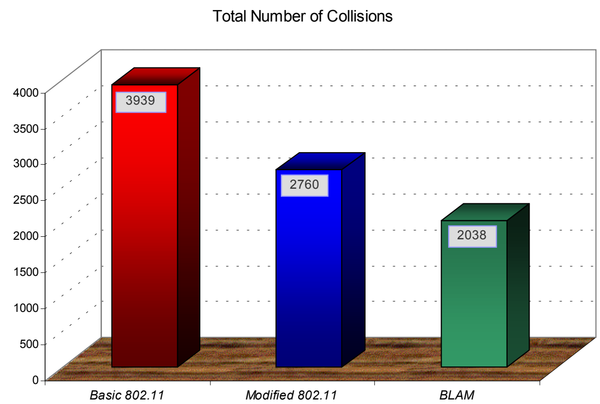


Fig. 12. Total Number of Collisions

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 links in the network are broken and no packets can be transmitted.

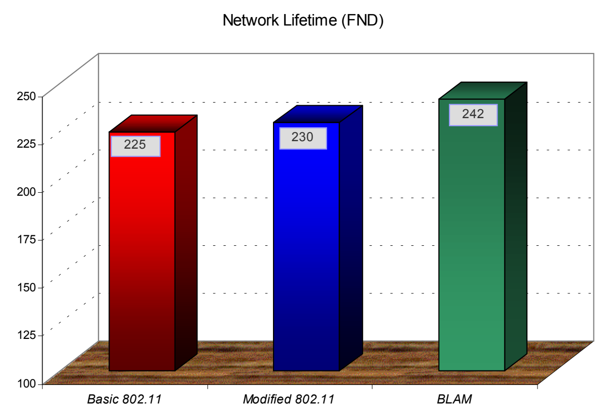


Fig. 13. Network Lifetime (in seconds)

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 13, the lifetime for BLAM is 15% more than that of the Basic 802.11 and 9% more than the Modified 802.11.

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,(as

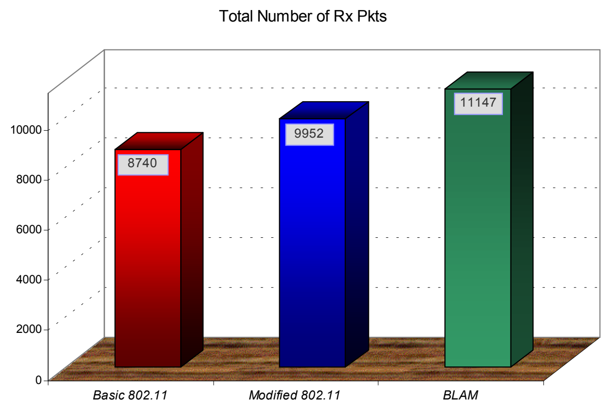


Fig. 14. Total Number of Received Packets

proved in the collision model, BLAM and IEEE 802.11 network throughput are almost equal) but rather forces them to decrease the number of retransmitted control frames (which saves energy and extends network lifetime). Moreover, since the network lifetime is extended, as discussed before, then more data packets are able to reach their final destinations during the useful operation time of the network. Figure 14 compares the total number of data packets that are correctly received by the destination application in the three MAC protocols. As shown in Figure 14, BLAM increased the total number of received data packets by 39% over the Basic 802.11 and by 16% over the Modified 802.11.

VII. Conclusion

In our work we used a collision model to analytically compare the behavior of BLAM and the IEEE 802.11 DCF protocols. We showed that the worst case probability of collision in BLAM is 13% higher than that of the IEEE 802.11 DCF, while in the best case a 4 folds improvement in the collision probability is achievable. We also showed that BLAM does not degrade the total network throughput, on the contrary, because the network lifetime is extended more data packets are received. We validated the correctness of the proposed model through simulation analysis for a single-hop adhoc network.

Moreover, for a single-hop network with 60 flows of CBR traffic, we show that BLAM when compared to IEEE 802.11 can achieve an 8% increase in the network lifetime and an increase of about 40% in the total number of received packets with a almost 50% decrease in the total number of collisions. This indicates that,in a real network traffic, the worst case of BLAM is not frequent.

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