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**Publication Date**

2006-10-09

# Bid Activation Multiple Access in Ad Hoc Networks

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***Abstract*— We present a new protocol for collision-free channel access in ad hoc networks called Bid Activation Multiple Access (BAMA). BAMA is based on bids made by nodes for slots within the context of probabilistic channel access. Winners of the bids for a given slot are determined as a result of a fair election of the bids for that slot. Nodes attempt to acquire varying number of slots depending on their traffic requirements. Nodes transmit their schedule information once in each frame prior to the data packet transmission in the slots acquired by them. Mismatched schedule information for a given slot are corrected based on the same fair election by the nodes that hear the schedule information. BAMA does not require explicit control information (HELLO packets) to build up local or global topology of the nodes to compute a transmission schedule for the nodes. The performance of BAMA is studied by simulations and compared against the performance of comparable protocols. It is found that BAMA provides better throughput and much lower end to end delay when compared to other protocols, both at low loads as well as high loads. The traffic adaptive nature of BAMA allows for the performance of BAMA to be largely independent of the network load. This makes it ideal for deployment in high bandwidth scenarios where low end to end delay is desirable.***

## I. INTRODUCTION

Real-time interactive applications have become increasingly popular over the internet. With the recent advances on video over IP and VoIP as an alternative to PSTN telephony, a greater focus has been placed over Voice and Video over Wireless IP. Mobile ad-hoc networks are extremely useful in disaster relief work and in the battlefield. Such scenarios have low delay requirements while maximizing throughput. Usage of real-time interactive applications in such disaster-relief and battlefield scenarios allows for quicker responses and better co-ordination. However, such real-time traffic (especially video) is not only delay sensitive but also consume a large amount of bandwidth.

Although a large number of channel access schemes have been developed for ad-hoc networks, they have been restrictive in their usage. For example, contention based schemes like CSMA[14] and CSMA/CA[8], which have been most commonly deployed in ad-hoc networks today, suffer from loss of utilization in increasingly higher loads. 802.11e[2] was designed to provide QoS support to allow for usage in real-time traffic scenarios. However, it was primarily designed for usage with a central base station and not for mobile ad hoc networks. Contention free schemes do not suffer from these problems, but fail to provide channel access delay guarantees which are required for such real-time traffic. Also, such schemes do not adapt to traffic changes within the nodes and hence fail to allocate the channel to nodes in a manner indicative of the traffic requirements at the nodes.

We propose the Bid Activation Multiple Access (BAMA) mechanism to attain high channel utilization and low packet delay at different loads. In BAMA, time is slotted and nodes bid for ownership of a slot by sending bid packets. Feedback on their bid status is obtained by schedule packets that are broadcast by the neighbors. Any conflict (multiple bids by different nodes for the same slot or mismatched schedule information) is resolved by using the Neighborhood-aware collision resolution scheme introduced in [12]. Each node bids on a varying number of data slots in a frame, in proportion to the traffic density at the node with respect to its two-hop neighborhood. Once a node wins a slot, it retains ownership of the slot in the following frame as long as its traffic density warrants ownership of the same number

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[1] This work was supported in part by the National Science Foundation under Grant CNS-0435522, by the Army Research Office under Grant W911NF-05-1-0246 and by the Baskin Chair of Computer Engineering at University of California, Santa Cruz.

1-4244-0507-6/06/$20.00

of slots. BAMA does not require any *Hello* mechanism to construct two-hop topology information nor does it require slot subdivision. It builds the information about the nodes that are involved in data transmission only.

We evaluate the performance of BAMA through simulations and compare it with the industry standard 802.11 [1], 802.11e[2] which is designed to provide QoS guarantees and TDMA. We find that BAMA outperforms all the other protocols under low to medium load, and as the network load increases, BAMA adapts better to the increased network load without degenerating much in performance. It provides much better end to end delay guarantees when compared to other protocols while keeping jitter under control and hence makes it suitable for supporting real-time interactive applications.

The rest of the paper is organized as follows: Section II summarizes previous work that has been done in this area. Section III provides more details of the protocol. Section IV then studies the performance of BAMA using simulations. Section V provides a summary of the work and concludes the paper.

## II. RELATED WORK

Among the contention-based schemes, ALOHA, CSMA[14] MACA[15], MACAW[21], FAMA[6] and IEEE 802.11 DCF [1] are the most representative ones. They are however suitable for light traffic load as under high load conditions, they suffer from a large number of collisions, and degenerate in their channel utilization. At high loads, contention-based schemes like MACA and IEEE 802.11 DCF starve certain nodes on account of repeated collisions and are unable to provide an upper bound on channel access time.

There exists prior work based on reservations-based scheduling. The Distributed packet reservation multiple access protocol (D-PRMA)[19] is one such attempt. However, it heavily favors voice-traffic, thereby making it unsuitable for integrated data and voice traffic. The five-phase reservation protocol (FPRP) [23] and MACA with piggy-backed reservations (MACA/PR)[4] were other reservation-based schemes which had the disadvantage of limiting the minimum size of the slot.

Contention-free schemes divide time into slots and attempt to assign the slots to nodes such that data transmissions do not collide and effective spatial reuse in achieved. These schemes require time synchronization. A generic unified framework for (T/F/C)DMA channel assignment in Manets named UxDMA, was proposed to compute a suboptimal k-coloring of a directed graph within polynomial steps[17]. A number of topology-transparent scheduling schemes [7],[9] have also been proposed where nodes transmit data frames in multiple time slots in a frame. However, Rentel and Kunz [16] have shown such schemes to provide an average throughput that is at best similar to slotted ALOHA.

There have also been topology dependent schemes. NAMA [12], HAMA [13], MALS [11], TRAMA [22], SEEDEX [18] are based on randomized channel access approaches which requires each node to maintain its two-hop information which is then used for slot assignment. Nodes either exchange their identities to their neighbors or the seeds of their proposed random transmission schedules which is used in an election to determine the priorities of the nodes for ownership of various slots. The limitation of these schemes is their inability to adapt to changing traffic conditions and inability to provide guarantees to channel access delays. There may also be chain effects where the priorities of the nodes cascade from higher priorities to lower priorities as discussed in [11].

### *A. Problems with interference from nodes which are more than two-hops away from the sender*

A common assumption of the physical layer which is made during the design of a number of MAC protocols is that packet losses are a result of concurrent transmissions in a two-hop neighborhood. Thus, if node A is sending data to node B, then as long as no node within the one-hop neighborhood of B, sends any signal during the data transmission of A, the data packet of A is received successfully. However, in a real physical channel, this assumption is incorrect. Other concurrent transmissions that occur more than one-hop away from B, may interfere with the data transmission from A to B. Radio transmissions from nodes which are more than one hop away from the receiver add to the noise levels and hence add to the interference signals at the receiver. B. F.Ye et.al [5] and K.Xu et.al [10] further study this problem on how the interference of transmissions which are more than two-hops away from the sender affect successful packet reception. IEEE 802.11 attempts to reduce the effect of this problem by mandating the receiver to send an Acknowledgement for each successful data reception. However, in scenarios with large traffic density in the network, this increases the density of radio signals in the network, thereby resulting in greater interference thereby contributing to the poor performance of 802.11 at higher loads as mentioned in [5]. The effect of such interference in scheduled channel access schemes is much higher as such schemes assume that if a node successful acquires the channel for the duration of the data transmission over a two-hop neighborhood, then, the packet would be successfully received by the recipient.

## III. BIDDING BASED CHANNEL ACCESS PROTOCOL DESCRIPTION

### *A. Channel Organization*

Time is slotted and 'k' slots make up a frame. We assume that time synchronization among the nodes is provided. Unlike other contention-free channel access schemes, in BAMA all the slots are initially contention based slots. The same slot may be assigned to more than one node if their concurrent transmissions do not collide. We assume that the number of slots 'k' in a frame is larger that the maximum number of nodes in a two-hop neighborhood. Each node maintains a list of slots that it has previously reserved for itself by participating in the bidding process in the prior frames. It transmits its data in a slot that it has been reserved for itself. In all other slots, it remains in reception mode. If a node requires more slots (on account of greater traffic in its queue), it participates in a bidding process to bid for slots are currently unreserved. If it wins the slot as a result of the bidding process, it then adds it to the list of slots that it has reserved for itself.

### *B. Bidding process*

For each slot in the frame, a node first decides if the slot has been reserved by itself, by any of the nodes in its two-hop neighborhood, or is unreserved. This information is maintained by each node in a slot assignment table. The owner identifiers for each slot are also maintained in the slot assignment table as these identifiers are required for the election process.

The set of one-hop neighbor nodes of a node $i$ is denoted by $N_i^1$. Accordingly, we can define the set of two-hop neighbors of node i as $N_i^2$=$\bigcup_{j \in N_i^1} N_j^1$. Nodes examine the size of their queue and determine their traffic weight. If, $q_i$ is the size of the queue of a node i in bytes. The traffic weight of a node i, given by $w_i$ is

$$w_i = \frac{q_i}{\sum q_j}, \forall j \in N_i^2 \bigcup N_i^1$$

The maximal number of slots that a node $i$ can acquire in a 2-hop neighborhood = (Number of slots in a frame - min) × $w_i$ where min represents a minimum number of free slots. This parameter is configurable. $Min \ll Number\,of\,slots\,in\,a\,frame$. This minimum required number of free slots allows for new nodes to send in their bids containing their traffic density information for this information to propagate in its two-hop neighborhood.

A nodes randomly select a slot $n$ that it believes to be free, and then bids for slot $n$, by sending a bid packet multiple times in the slot $n$. Feedback on the bid is obtained from its neighbors in the subsequent slots. Now, if the slot $n$ is allocated to the given node, the node does not face any further contention for slot $n$. A node could bid on multiple slots depending on its traffic weight.

After acquiring a slot, the node sends out the schedule information that it has learnt in the slot that it has reserved for itself. Subsequently, after the schedule packet transmission, if the data transmission time for a data frame does not exceed the slot boundary, it sends out data packets in the same slot. Schedule information packets are sent out only once in a frame. Election for a slot is conducted using the Neighborhood Collision resolution(NCR) which was introduced in NAMA[12]. NCR uses a $hash(i,t)$ to compute a pseudo-random number representing node i's priority at time t. We use the same algorithm with the parameter $t$ representing the priority of the node $i$ in slot $t$. Let $contenders_t$ be the nodes which contend for a slot t. More than one node could be in a contention set either if more than one node chooses the same slot for bidding or if the schedule information is incorrect. Each of the neighbors compute the owner node for each slot, and then broadcast this information in the first of their owned slots. A node which has previously bid for a slot, thus, gets feedback on its bid status by listening to the schedule packets being broadcast. This process reserves a slot for a given node. Since, the identifier for the nodes which own a

**Algorithm 1** Election algorithm(node i)

```
for each slot t in frame do
  for each x $\in contenders_t$ do
    $prio_x$ = hash(x $\oplus$ t) $\oplus$ x;
    if $prio_x >$ MaxPrior then
      MaxPrior=$prio_x$;
      OwnerNode(t)=x;
    end if
  end for
  if OwnerNode(t) == i then
    Add t to $MySlots_i$;
  end if
  Add OwnerNode(t) to slot status table;
  Erase all nodes in $contenders_t$ except OwnerNode(t);
end for
```

particular slot are included in the schedule packet, any node which has mismatched information, will use the same election algorithm to determine the ownership of the slot.

### C. Schedule distribution

A node maintains a list of neighbors by listening to frame transmissions. Any node which sends out any packets is listed to be a neighbor. A node includes the schedule information of all its 2-hop neighbors. It does so by sending out the schedule information of any node which it lists to be a one-hop neighbor. If there exists four nodes A–B–C–D, B lists A & C as neighbors and sends out information about the slots that are held by A & C. However, A is not included in the neighbor set of C, and hence C does not include the schedule information of A in its schedule packets. Thus, D does not learn of the slots held by A and can bid on those slots. This mechanism of schedule distribution ensures that the cascading priorities problem which exists in NAMA does not occur here as the priorities of A and D are mutually independent.

Each bid process has an expiration period which is specified in units of number of frames. If no schedule packet is transmitted during this period, the node which initiated the bid assumes successful reservation from the bid.

### D. Activated Nodes

A node which broadcasts its schedule information in a frame is called an activated node. Trivially, all nodes which have data to be transmitted will need to be activated nodes. In addition, any node which is the recipient of data will need to be activated. Hence, each node maintains a list of activated neighbors. A scenario is outlined in figure 1. If the node B has no traffic, then it would not have any slots assigned to itself. Hence, when A and C send out bid packets, B will not notify them of the slot assignment conflict. However since B is the recipient of data, A and C will request activation. Hence, B will bid and assign a minimum of one slot to broadcast its schedule information. This prevents the such a slot assignment conflict. If a node needs to send out a broadcast packet, then it requests activation of all its one-hop neighbors by using the broadcast address. This prevents the hidden terminal problem.

On the other hand, if there exists nodes which donot require activation, like the node E in figure 2, they will not bid for any slot, as they are not required for maintaining correct schedule information. This results in better usage of the slots for only those nodes which need to send out their schedule information to maintain correct schedule bid for slots.

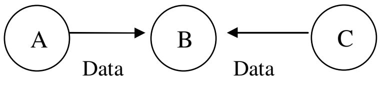


Fig. 1. An example scenario

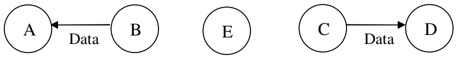


Fig. 2. An example scenario

### E. Handling conflicts

In the scenario shown in the figure 3, two nodes 3 and 5 select the same slot k for a bid. Node 2 does not hear the bid packet from 5, and hence assigns the slot k to node 3. However, node 4 hears both bid packets of both 3 and 5, computes $Priori_3$ and $Priori_5$ and assigns the slot k to the winner(assume $Priori_5 > Priori_3$, hence the winner is node 5). Node 3 hears the schedule information broadcast by node 2 which specifies that it is the owner of k. It also hears the schedule information broadcast by node 4 which specifies node 5 as the owner of k. It computes $Priori_3$ and $Priori_5$ for the slot k. Since $Priori_5 > Priori_3$, it assigns k to node 5. Node 3, in its schedule information does not include slot k as occupied, and hence node 2 is free to bid for slot k.

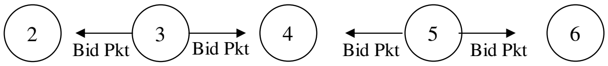


Fig. 3. An example scenario

### F. Retaining and dropping slot reservation

Each node retains the slots assigned to itself for the subsequent frames. Each slot assignment has a valid time to live associated with it. This value is decremented at the beginning of each frame and reset to its initial value if data is transmitted in it. At the beginning of each frame, a node A re-computes its schedule information and checks if the number of slots that it holds is more than what its traffic weight has allowed. If node A holds more slots that what its traffic weight entails, it randomly selects a slot from among the slots that it owns and drops it. It propagates this information to its neighborhood in its schedule information. This allows for traffic adaptive usage of slots by the nodes.

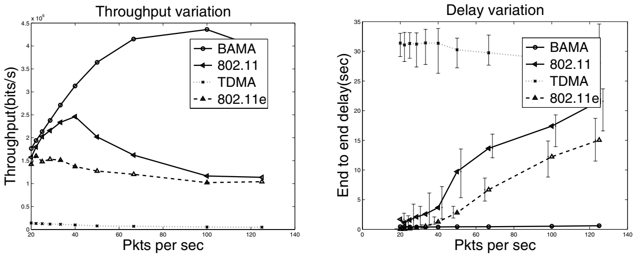
### *G. Multiple paths to the destination*

Despite the successful assignment of slots across a two-hop neighborhood, some of the packets may not be received successful by the receiver because of the interference effects in the physical medium. Repeated transmissions from the sender is not an optimal solution as the node which is more than two-hops away that interfered with the initial data transmission would continue interfering in subsequent frames to the data packet retransmissions. We take advantage of the nature of the wireless medium to help offset the effects of this problem. Since, wireless links are broadcast in nature, other nodes one-hop away from the intended receiver may receive the initial data transmission successfully. If some of these nodes do not have data to send in their assigned slots(part of the slot was utilized for data transmission but there exists unused parts, or slots were used only for schedule transmission), they could attempt retransmitting this data to the destination.

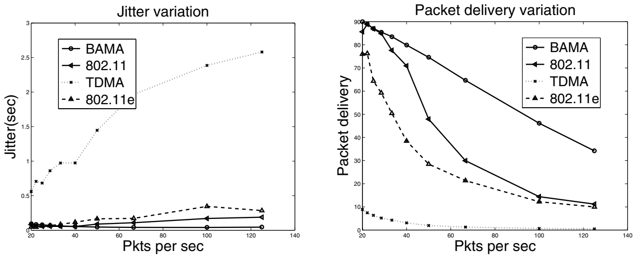
## IV. SIMULATION RESULTS

Simulations for BAMA are conducted using the Qualnet simulator[20].Simulations are conducted with 50 nodes uniformly distributed across a 400 × 400 square meters in a static topology. The physical layer adopted is the 802.11a physical layer operating at 54 Mbps. A time slot is 0.5 milliseconds. This is large enough to transmit a MAC data frame of more than 1500 bytes (as this is the MTU assumed by most of the IP networks). One thousand time slots make up a frame. Thus, frame duration = 1000 × 0.5ms = 0.5 seconds. The duration of the simulation is 90 seconds (equal to 180000 time slots). For BAMA, data retransmissions are done once in addition to the initial data transmission. The transmit power is set to 17 dBm, receive sensitivity to -69 dBm. The routing protocol used is OLSR[3] which is allowed to run for 15 seconds without any additional data traffic for the route discovery.

Twenty four Constant Bit Rate (CBR) flows with the same IP precedence bits are pumped between nodes with varying inter-packet times. The senders and destinations are chosen randomly but it is ensured that they are more than two-hops away from each other. This ensures that the metrics measured are metrics which are reflective of multi-hop traffic. The simulations are repeated with eight different seeds to average the results for each scenario.Traffic is pumped after 15 seconds. The mobility simulations are conducted by using a random-waypoint model with the way point speeds randomly varying from 1 to 15 meters/second and a pause time of 10 seconds.



(a) Net flow throughput (b) Delay



(c) Jitter (d) Packet Delivery

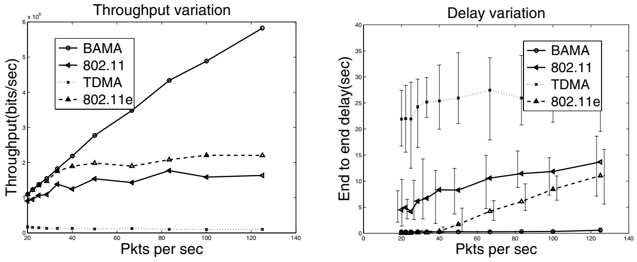
Fig. 4. Static topology

Figures 4(a) - 4(d) shows the variation of the various metrics on increasing the traffic load in a static network. Figures 5(a) - 5(d) show the variation of the metrics on increasing the traffic load in a mobile network. We have also shown the minimum and maximum delays over all the seeds as errorbars for each of the protocols. We see that under light loads, BAMA performs in a manner similar to 802.11 and 802.11e, but with increase in the load in the network, both of the contention based protocols begin to perform badly. As we see, the end to end delay performance of BAMA remains largely constant. Slight increase in seen at extremely large loads on account of greater queuing delay at the nodes.

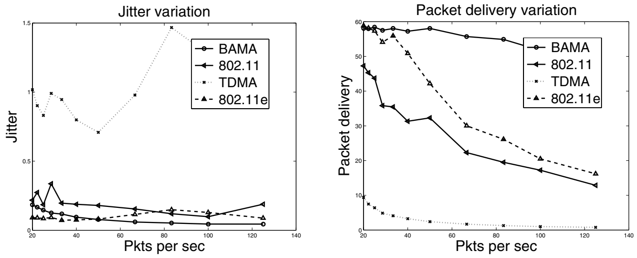
To study the behavior of TCP traffic existing in the network along with CBR traffic, we introduce TCP traffic. 12 FTP flows are pumped into the network along with 12 CBR flows. TCP RENO with Selective ACKs was used with the window scaling options mentioned in RFC 1323. For the simulations with TCP, the physical layer is assumed to be ideal. Hence, packet loss is due to collisions only. This is to prevent any other physical layer problems (like interference from more than 2 hops away) from incorrectly triggering congestion control mechanisms in TCP. The results indicate that BAMA performs well with TCP traffic as well.

## V. CONCLUSION

We have presented a contention-free channel access scheme which is suitable for low as well as high load

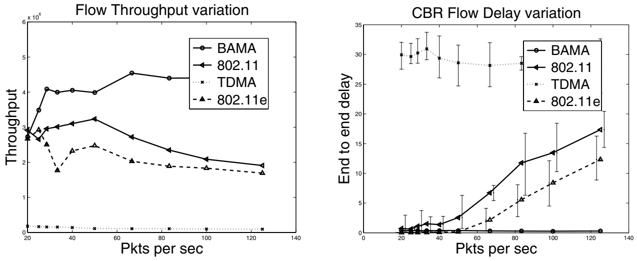


(a) Net flow throughput (b) Delay



(c) Jitter (d) Packet Delivery

Fig. 5. Mobile topology



(a) Net flow throughput (b) Delay

Fig. 6. CBR + TCP traffic (Static topology)

conditions. Because of the its ability to avoid collisions and its traffic adaptiveness, BAMA avoids the unfairness problems of IEEE 802.11 DCF. It has been shown that BAMA performs better when compared to both IEEE 802.11 as well as IEEE 802.11e. In addition, it requires only the nodes which are required to participate for successful data transmission to be activated. This is a key differentiating point from other contention-free scheduling schemes which results in more optimal use of the channel.

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