An Integrated TDMA-Based MAC and Routing Solution for Airborne Backbone Networks Using Directional Antennas

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***Abstract*—Airborne backbone networks are useful in tactical applications to interconnect tactical sub-networks. Major challenge in such networks which normally comprise large numbers of highly mobile nodes lie in the design of medium access control (MAC) and routing protocols that can accommodate scalability and the highly dynamic topology. In this work, we propose an integrated solution of time division multiple access (TDMA) based MAC and routing protocols, both of which use the attributes of a clustering scheme, where clustering was adopted to address scalability. While the clustering scheme also establishes proactive routes between cluster clients and cluster head, the reactive routing protocol uses both the cluster attributes and the proactive routes within the cluster to address the challenges of high dynamics in the airborne network. The MAC is equipped with TDMA scheduler for operation with directional antennas used in the airborne nodes to provide spatial reuse. We assess the performance of the proposed integrated solution in terms of success rate and latency in packet delivery.**

Keywords-Airborne Backbone Network, Cluster formation, TDMA, Routing, MAC, Directional Antennas

I. INTRODUCTION

Backbone networks formed by airborne nodes such as *unmanned aerial vehicles* (UAVs) are of significant importance in tactical applications as they can be used to connect several tactical sub-networks which are at distance from one another. Such airborne nodes have significant processing and computation capabilities and can be equipped with directional antennas Though the targeted application is that of a backbone network, we limit our contribution to demonstrating the capability of the airborne backbone network to forward data reliably between two distant nodes in the backbone network, which could serve as the gateway points to two distant sub-networks.

Airborne backbone networks comprise large number of mobile nodes at speeds ranging from 200 to 300 km/h making scalability and highly dynamic topology two of the main challenges for designing an efficient solution. The contribution of this work is to provide an integrated solution of TDMA-Based MAC and routing protocols that can overcome previous challenges through following features:

- Clustering: was adopted to address scalability. We assume that cluster heads (CHs) are pre-assigned to last for entire mission duration. A cluster contains one CH and several cluster clients (CCs). Proactive routes are formed within a cluster, while routes across clusters are maintained reactively.
- Multiple redundant proactive routes: are formed between a CC and its CH so that if one route is lost another is ready to use, thus supporting dynamic topology. These routes are formed using the *Meshed Tree algorithm* [1] which simplifies proactive route formation and maintenance thanks to its unique naming scheme.
- Reactive routes: are maintained as a sequence of clusters, hence, reactive route discovery and maintenance is done at cluster level. This adds resiliency against mobility since reactive routes are not dependent on specific nodes, in addition to reducing control message flooding. Since reactive routes are concatenation of proactive routes which are continually updated with node mobility, the probability of stale reactive routes is low.
- Hybrid time division multiple access (TDMA) scheduler: is adopted by the MAC and uses the attributes of a multi hop clustering scheme to schedule time slots for CCs in the cluster. The scheduler uses directional antennas and is aware of the routing mechanism and proactive routes naming scheme within the cluster; hence schedules slots for data routing from CH to CCs and CCs to CH in an efficient manner providing spatial reuse.

The paper is organized as follows. In Section II, we highlight related work in the area of cluster based routing and TDMA scheduling. In Section III, we provide details of the physical layer. An abbreviated description of the meshed tree clustering scheme is provided in Section IV, followed by the proposed solution description including the proactive, reactive routing protocol and the TDMA scheduler. In Section V, simulation details with results and performance analysis are presented. Section VI provides concluding remarks and planned future work.

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II. RELATED WORK

In this section, we present some work related to cluster based routing and TDMA scheduling. Though our solution combines both schemes effectively, a similar approach is not available in the literature to the best of our knowledge. Hence the first part of the related work deals with cluster based routing. This topic has been researched extensively; we present only those closely related to our approach. The second part of related work deals with TDMA schedulers, especially the ones that use directional antennas and leverage spatial reuse, as they are closely related to our approach.

A. Cluster Based Routing

Several reviews are available that compare across different types of routing protocols [2-6], namely proactive, reactive and hybrid routing protocols. Reactive and hybrid routing protocols are desirable when communications between distant nodes in a MANET are required and the MANET is not very dense. In reactive routing protocols a source node discovers and maintains several cached routes to a destination node. As mobility increases, route caching becomes ineffective as pre-discovered routes break down, requiring repeated route discoveries [10].

Partitioning the MANET through clustering and zoning is useful to limit control messages and also to address scalability. Hybrid routing protocols normally adopt zoning or clustering, and then use proactive routing protocols within the zone and reactive routing protocols to communicate with nodes outside of a zone. The *Zone Routing Protocol* (ZRP) [11] is one such hybrid routing protocol, where each node has a pre-defined zone centered at itself. ZRP proposes a framework, whereby any proactive routing protocol can be adopted within the zone and any reactive routing protocol can be adopted to communicate outside of the zone. Multi path distance vector zone routing protocol (MDVZRP) [12] is an implementation of ZRP that uses multi path *Destination Sequence Distance Vector* (DSDV) [9] for proactive routing and *Ad-hoc On-demand Distance Vector* (AODV) [7] for reactive routing. *LANMAR* [13] routing protocol defines logical groups to address scalability where by landmark nodes keep track of the groups. A local scope routing scheme based on *Fisheye State Routing* is used in the group. To forward outside the scope, packets are routed towards the landmark in the destination's logical group. In *Hybrid Cluster Routing* [14] multi-hop clusters are established. However in this case intra-cluster uses a reactive routing scheme similar to AODV and *Dynamic Source Routing*,[8] while inter cluster maintenance is done proactively.

Our Approach: is a hybrid cluster based routing protocol. Using the *Meshed Tree algorithm* proactive routes are formed between CCs and CHs. For routing across clusters a reactive routing approach at cluster level, which uses concatenations of proactive routes within the clusters, is adopted. We argue that our approach is different in adopting the *Meshed Tree algorithm* for cluster formation which uses a unique proactive route naming scheme. In more details each route is given a virtual ID (VID) which reveals current route topology information simplifying the task of forming and maintaining routes and helps in calculating efficient TDMA schedules.

B. Schedulers: Time Division Multiple Access

TDMA scheduling requires strict time synchronization among participating nodes [15]. In addition, if the nodes are mobile, periodic changes in the network topology require updated TDM schedules, to be computed, preferably with low complexity and propagated to all concerned nodes in a timely and an efficient manner.

A major challenge in the design of a TDMA scheduler is the generation of schedules. Several algorithms directed towards scheduling can be noted in the literature [16]. Scheduling algorithms fall under two main categories distributed or centralized. In the centralized approach, scheduling is performed by a scheduler that gathers information about all nodes and their links to compute the schedule. This is a difficult task to achieve in a timely and resource efficient manner, especially with large numbers of mobile nodes. On the other hand, distributed scheduling requires complex algorithms with intelligence to enable each node to decide their schedules with minimal conflicts.

Our Approach uses hybrid scheduling, which is possible due to the cluster based approach. Within a cluster the CH is the scheduler that decides the transmission reception schedules for its CCs. However each cluster's schedule is determined independently by its CH giving conflict consideration only to those CCs that are bordering two or more clusters thus making it distributed across clusters. Given that *link assignment strategies* are efficient if employed with directional antennas [15] and as the proposed clustering scheme has such link information available in a cluster we decided to adopt this type of assignment strategy. However, our approach is different in using topology information contained in proactive route naming scheme to calculate efficient TDMA schedule and maximize spatial reuse with the aid of directional antennas.

III. THE PHYSICAL LAYER

In this section, we describe the operational features of the directional antenna system used at the physical layer. All nodes in the airborne network can be equipped with four phased array antennas capable of forming two beam widths. One is focused with a beam angle of 10^o and the other is defocused with a beam angle of 90^o. In the focused beam mode the data rate is 50 Mbps and in the defocused mode the data rate is 1.5 Mbps. Each antenna array covers a quadrant and is independently steerable to focus in a particular direction within that quadrant in the focused beam mode.

We assume each node is equipped with Global Positioning System (GPS) to provide node position. Every node appends its GPS location in the packets it transmits. Receiving (neighbor) nodes log and continuously update a "location" cache with the transmitting node's location. The cache stores a maximum of the last three positions of any node. Cached location information is used to track and estimate the current location of neighboring nodes during packet transmission. The estimated location of a receiver node is used, by a transmitting node, to control the transmit power and form a directed beam to the receiver node by using the most appropriate of its phased array antennas.

GPS is also used for time synchronization, and we assume that all nodes are synchronized to time slot boundaries and the beginning of new frames. However, a guard time is included in each time slot to offset synchronization errors as well as to allow for beam switching.

IV. MESHED TREE CLUSTERS

It is important to understand the meshed tree cluster formation and proactive routing within the cluster as they are used both by the scheduling algorithm and reactive routing protocol. The clustering scheme adopted in this work, forms multi hop clusters using the *Meshed Tree algorithm* [1], where the root of the meshed tree is at the CH. A single 'meshed tree' cluster formation is described with the aid of Figure 1.

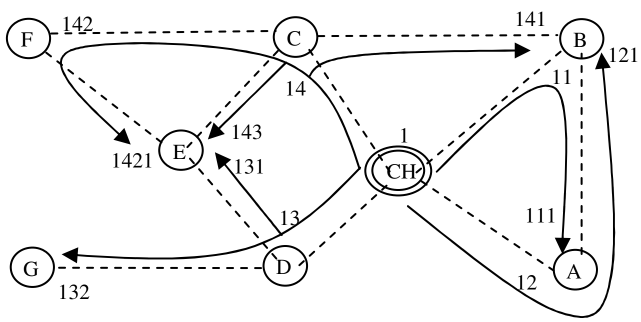

Figure 1. Cluster Formation Based on Meshed Trees

The dotted lines connect nodes that are in communication range with one another at the physical layer. The cluster head is labeled 'CH'. Nodes A to G are the CCs. For simplicity in explanation, the meshed tree formation is restricted to nodes that are connected to the CH, by a maximum of 3 hops. At each node several 'values or IDs' have been noted. These are the virtual IDs (VIDs) assigned to the CC defining branches, proactive routes, linking it with its CH. Assuming that the CH has a VID '1', all its CCs have '1' as a prefix in their VIDs. Any CC that attaches to a branch is assigned a VID, which will inherit the prefix from its parent node, followed by an integer, which indicates the child number under that parent. In this work we limit the number of children to nine and use a single digit without loss of generality.

A. Proactive Routes in the Cluster

In Figure 1, each branch is a sequence of VIDs that is assigned to CCs connecting at different points of the branch. The branches of the meshed tree thus provide the ***route*** to send and receive data and control packets between the CCs and the CH. The branch denoted by VIDs 14, 142 and 1421, connects nodes C (via VID 14), F (via VID 142) and E (via VID 1421) respectively to the CH.

Consider packet forwarding based on VIDs in which the CH has a packet to send to node E. If the CH decided to use E's VID 1421, it will include this as the destination address and broadcast the packet. Enroute nodes C then F will pick up the packet and forward to E. This is possible as the VIDs for nodes C and F are contained in E's VID. The VID of a node thus provides a virtual path vector from the CH to itself. Note that the CH could have also used VIDs 143 or 131 for node E, in which case the path taken by the packet would have been CH-C-E or CH-D-E respectively. Thus between the CH and node E there are multiple routes as identified by the multiple VIDs. The support for multiple routes through the multiple VIDs, allows for robust and ***dynamic route adaptability*** to topology changes in the cluster, as the nodes can request for new VIDs and join different branches as their neighbors change.

B. Inter-cluster Reactive Routing

Nodes bordering two or more clusters are allowed to join the branches originating from different CHs, and will accordingly inform their respective CHs about their multiple VIDs under the different clusters. This information will enable the CHs to avoid conflicts when scheduling timeslots for such border nodes. Also by allowing nodes to belong to multiple clusters, the single meshed tree cluster can be extended to *multiple* overlapping *meshed tree* (MMT) clusters to cover a wider area and address *scalability.*

A node that has to discover a route to a distant node sends a 'route request' message to its CH(s). The CH then identifies the neighboring clusters based on updates from border nodes and forwards a copy of the 'route request' message to the border node, so that they can forward to the CH in the next cluster. The 'route request' message however has an entry for all the clusters that will be receiving the message, to avoid looping of the message. Thus the route request is not forwarded by all nodes, but only by all clusters and follows a path CH-border node- CH and so on.

When the CH of the destination node receives the route request, it will forward the route request directly to the destination node. The clusters forwarding the route request record the original sending node and the last cluster that the route request came from; this information is useful in forwarding the route response message when it returns. The destination node generates the route response and sends to its CH, which then forwards it back to the CH in the originating cluster and the source node along the same *cluster path* the route request took. Along the path back, all forwarding CHs will record the previous cluster and original sender of the route reply. The route between the sender and the destination node is thus initially set up as a sequence of CHs, but maintained as next cluster information. Mobility of nodes does not impact the reactively discovered route, as long as the CHs exist. Note that movement of CHs also does not impact the reactive routes.

C. Scheduling in the Cluster

The meshed tree cluster is formed in a distributed manner, where a node listens to its neighbor nodes advertising their VIDs, and decides to join any or all of the branches. Once a node decides to join a branch, it informs the CH, who registers the node as its CC and confirms its admittance to the cluster and accordingly updates a VID table of its CCs as shown in Table 1 for the cluster in Figure 1. Thus the 'meshed tree' cluster formation allows a CH to control the nodes it accepts; i.e., a CH can restrict admittance of nodes who are within a certain number of hops and not dmit new nodes to keep the number of CCs in the cluster under a certain value. This is useful to contain the scheduling zone of the CH.

TABLE I. CLUSTER CLIENT'S VIDs LIST AT CH

Node	Multiple VIDs
A	12, 111
B	11, 121, 141
C	14
D	13
E	131, 143, 1421
F	142
G	132

From the *Cluster Client's* VID table, implicit topology information is available to the CH; for example node B has a VID 1421, indicates that it has a link to the node with VID 142. The CH will use this information and its capabilities of controlling and communicating with the CCs to establish recurring time frames with a time slot scheduled for transmission and reception on the links between CCs and between CCs and CH in the cluster. As nodes, join and leave a cluster, the CH updates this table and announces the new schedule. Thus the scheduling operations are closely integrated with the cluster formation process.

D. Slots and Functions

A frame comprises of control and data slots. In this work four slots are preselected for control purposes. These slots are used by nodes to advertise their VIDs, and other broadcast information; and also to listen to advertisement by neighbor nodes. Remaining slots are used for transferring data packets and other control packets between CCs and CH. From a node's perspective, assigned data slots can either be used for reception or transmission using focused beams.

Slots that are not assigned to be either control or data slots are considered temporary slots. Nodes may use such temp slots to transmit packets when they do not have an assigned data slot yet, such as during the registration process. When a node does not have anything to send on a temp slot, it will listen for any incoming transmissions. At any time these slots can be changed to an assigned data slot by the CH.

The cluster schedule is distributed by the CH to all CCs in the cluster at the start of a frame with "beacon" packets. Each CC independently chooses the 'best' (in our case shortest, which is decided on the VID length) route to forward the beacon packet using meshed tree's routing information. Schedules for a given frame are transmitted one frame ahead to allow enough time for the beacon packets to reach nodes that are at the maximum hops from the CH.

E. Sample Schedule

A sample schedule generated by the proposed scheduler is given in Table 2. Each column is a slot; we show only 12 slots, which is a partial frame. In the first column are the node's unique IDs, which in this case are the alphabets we used for identifying the CCs in Figure 1. In each column we mark the VID of the sending and the receiving nodes, and the arrow shows the direction of transmission. For example in slot 1 CH (VID '1') sends to node A with VID '11'. The slot allocation process, proceeds by allocating slots for the CH to 1 hop nodes, followed by the 1 hop CCs sending to their 2 hop children and the 2 hop CCs sending to their 3 hop children and so on. However, due to the directional antennas used we can have simultaneous transmission between two pairs of distinct nodes; for example in slot 3 CH is sending to node D on VID 13, but node B using VID '11' is sending to node A at VID '111'. A closer look at the schedule will reveal that the flow from the outer leaf nodes to the CH is the mirror of the allocation process from CH to leaf nodes i.e., the 1[st] hop children are allocated the last time slots in the frame.

TABLE II. SAMPLE SCHEDULE PROVIDED BY CH

slot	1	2	3	4	5	6	7	8	Control messages	38	39	40
CH	1	1		1						1	1	1
A		12	111	12						111	12	
B	11		11	121	141					11		11
C				14	14	14	14					
D			13	13	13					13		
E							143	1421				
F				131		142		142				
G					132							

Data flow from CH to CCs in outward direction — Data flow from CCs to CH

V. SIMULATION RESULTS

We conducted simulations using OPNET for 20, 50 and 75 node multi-hop networks. All nodes were randomly assigned clockwise and counter-clockwise circular trajectories, with 100 Km radius and speeds varying between 200, 250, 300, and 350 Km/h at 20000 m altitude. The circular trajectories provide a stressful test as they result in many route breaks.

The frames had 28 slots each for the 20 and 50 node scenario, and 42 slots for the 75 node scenario, because the meshing in the cluster, results in most nodes using up all 6 VIDs and hence requires more slots, which is being optimized. Each slot had a 12.5ms duration and a guard time of 1.5 ms. The cluster size was maintained at 12 with a maximum of 3 hop distance between a CC and CH, and the most VIDs a node could have was set at 6.

Nodes in the network were randomly selected to send 1 MB file simultaneously, in 2 KB packet sizes to destination nodes also randomly selected. We measured overhead, average hops, successful packet delivery rate, as well as mean packet latencies, where;

- *Success rate* was calculated as the number of packets delivered to the destination node successfully as a percentage of the number of packets that originated at the sender node

- *Overhead* was calculated as the ratio of control bits to the sum of control and data bits during data delivery.

Each simulation was run with several seeds and the average values were plotted in the graphs shown in Figures 2-7. As there are no published results for such network scenarios to the best of our knowledge, we use the graphs to highlight the performance of the proposed solution.

A. 20 Nodes Scenario

The number of such sending nodes were varied from 4, 8 to 16 nodes. In the case of 16 senders, all CCs were sending 1 MByte files to all other CCs in the network, which is stress test case.

From Figure 2, the success rate was around 97% with 4 senders and dropped to 94% with all 16 senders. With increasing traffic in the network, one notices the reduction in the overhead; this is due to the inverse relationship between the traffic load in the network with respect to the control bits generated. In Figure 3, the average packet latency increased from 0.7 second to 3 seconds, when the traffic in the network increased. We recorded the average hops encountered between sending and receiving nodes to get an indication of the distance between the communicating nodes as it affects the success rate and overhead in the network. However in this case the recorded average hops was around 3.5 hops

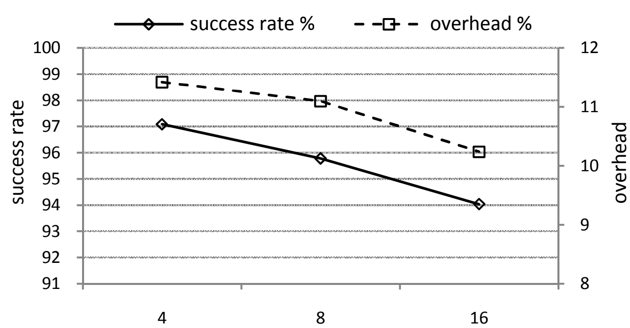

Figure 2. Success Rate and Overhead vs. Number of Senders

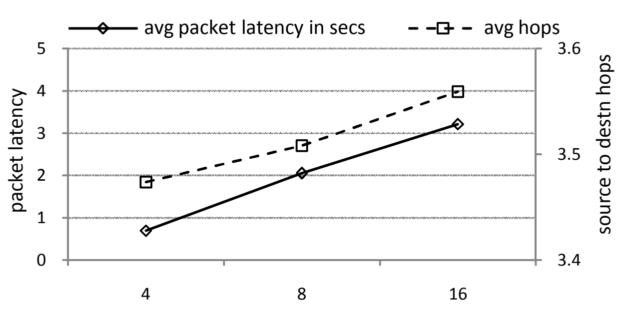

Figure 3. Packet Latency and Average Hops vs. Number of Senders

B. 50 Nodes Scenario

In this network scenario, the number of simultaneously sending nodes was varied from 10, 20 to 40. There were 10 CHs in this scenario hence with 40 sending nodes, all CCs were sending to all other CCs in the network. The success rate was 94% with 10 senders, and dropped to around 83% with 40 senders as shown in Figure 4. The overhead recorded is around 23%, which is higher than the 20 node scenario and can be attributed to the increase in route discovery maintenance across 50 nodes. In Figure 5, the average packet latency was recorded as 2.5 seconds with 10 senders and 11 seconds with 30 senders, which is reasonable to assume with the increased traffic in the network. The average hops recorded were between 6 to 7. The consistency in performance and the graph trends can be considered to be indicative of the stability of the proposed algorithms and the models.

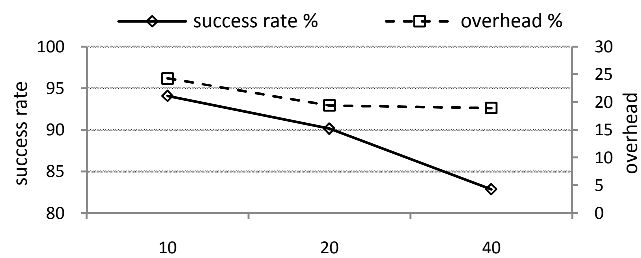

Figure 4. Success Rate and Overhead vs. Number of Senders

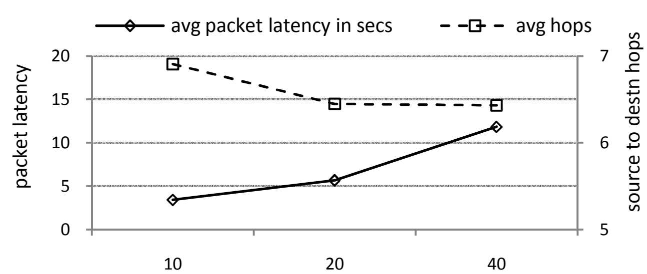

Figure 5. Packet Latency and Average Hops vs. Number of Senders

C. 75 Node Scenario

In this scenario we varied the number of senders from 15, 30 and 60 nodes. As the number of CHs was 15, in this case again we had all nodes sending traffic to all other destination nodes. The success rate shown in Figure 6 was 90% at 15 senders, which dropped to 70% with all 60 senders. The overhead was recorded to vary from 27 to 30%. In Figure 7, An increase in average packet latency can be noticed, which can be attributed to the increased traffic in the network.

D. Summary of Results

As stated earlier, due to the uniqueness of our approach we are unable to provide comparison with similar work conducted for airborne backbone networks. Furthermore, to the best of our knowledge, such stressful MANET scenario evaluations are also not available in the literature, because of which we present results, based on some targeted goals.

These being a high value of successfully delivered packets with some acceptable latencies, based on the traffic

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in the network. High success rate is difficult to achieve in such highly dynamic MANETs, especially when the number of mobile nodes is also high – several tens in this case. This is a good performance assessment if the type of data is files.

As part of our future work, we plan to extend the work to real time services, as an airborne backbone network is expected to carry different types of traffic, which originate from its subnets, which could be ground troops, UAVs performing surveillance amongst others. This will include prioritization of traffic while forwarding at the MAC layer. Future work will also involve optimizing our slot assignment algorithm, evaluating for various slot sizes, varying number of frame sizes and cluster sizes. We also plan to investigate the impacts of meshing (intra-cluster and inter-cluster), which can be controlled by the number of VIDs and the criteria used by CCs to acquire a VID.

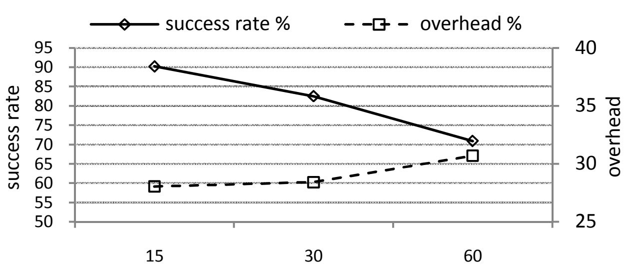

Figure 6. Success Rate and Overhead vs. Number of Senders

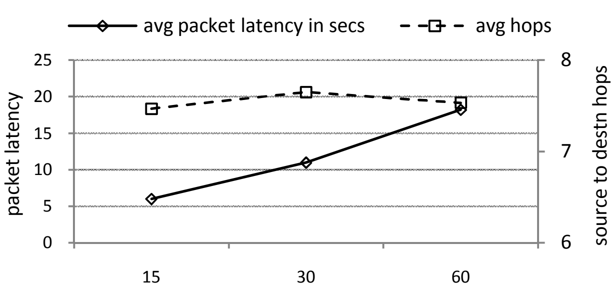

Figure 7. Packet Latency and Average Hops vs. Number of Senders

VI. CONCLUSION

We presented an integrated TDMA-Based MAC and routing protocol in this work, both of which were based on a meshed tree algorithm. The solution is unique both from the perspective of the TDMA scheduler and the routing protocol. The preliminary evaluations of this scheme show the very promising results that were obtained for airborne backbone networks. The consistent performance is also indicative of the stability of the proposed algorithms

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