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A Time-Slotted On-Demand Routing Protocol for Mobile Ad Hoc Unmanned Vehicle Systems

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Abstract— **Successful deployment of Unmanned Vehicle Systems (UVS) in military operations has increased their popularity and utility. The ability to sustain reliable mobile ad hoc formations dramatically enhances the usefulness and performance of UVS. Formation movement increases the amount of ground coverage in less time, decreases fuel consumption of the individual nodes, and provides an avenue for mission expansion through cooperative maneuvers such as refueling.**

In this paper, we study the wireless communication demands that arise from formation and maintenance of UVS within the context of a mobile ad hoc network (MANET). A MANET in formation is typically characterized by tradeoffs between network congestion and the ability to maintain useable communication bandwidth. Maintenance of UVS formations requires each node in the network to be peer-aware, which places a heavy demand on inner node communication.

In order to mitigate the inner node network congestion, we introduce a time-slotted communication protocol. The protocol assigns time-slots and allows the designated nodes to communicate directly with other peer-nodes. This approach has been introduced within the context of the Time-Slotted Aloha protocol for station-to-station communication. The approach taken here is to embed the time-slotted reservation protocol into a standard on-demand routing protocol to also address the need to reactively and proactively respond to formation maintenance.

The time-slotted on-demand routing protocol is shown to eliminate collisions due to route determination and, therefore, enhance quality of service as well as ensure necessary support for formation movement. A worst-case scenario is described and simulations performed to comparatively demonstrate the advantages of the new protocol.

Index Terms—**Ad Hoc On-Demand Distance Vector Routing AODV, Sub-Clustered Networks, Mobile Ad Hoc Networks, Unmanned Vehicle Systems, Time-slotted communications protocol.**

1. INTRODUCTION

The popularity of Unmanned Vehicle Systems (UVS) has increased dramatically because of their successful deployment in military operations, their ability to preserve human life, and the continual improvements in wireless communication serves to increase their capabilities. The usefulness of UVS such as Unmanned Aerial Vehicles (UAV) would be substantially improved if formation flight were added to the list of capabilities.

Formation flight is a complex operation that requires correction for wind gusts and terrain changes and in-flight pattern adjustment while allowing for a heterogeneous UAV network. When UAVs are viewed as nodes in a Mobile Adhoc Network (MANET), it is necessary to automatically coordinate the nodes within a formation while maintaining sufficient communication to support the mission. As the name infers, a MANET represents a loosely connected wireless network of nodes where a source node communicates with a destination node through an ad hoc communication network. This network is formed by discovering nodes within a one hop radio range from each other that link the source node to the destination node. In such a network, nodes may move in or out of radio range. In particular, when nodes move out of the ad hoc communication network the lost link must be replaced (repaired) by another alternate neighboring node to reconnect and complete the communication path between the source and destination nodes. The process of link failure and link discovery increases the burden on the network communications and can severely limit the success and capacity of formation flight. Formation flight provides the ability to cover a larger area of terrain eliminating redundant coverage and requiring less fuel and equipment resources. Sustained formation flight with a limited size cluster of UAVs has been achieved. The Multi-UAV Testbed operated by the Massachusetts Institute of Technology maintained formation with two nodes [1].

Network congestion severely limits the quality of service for MANET communications. The process of maintaining a route in the event of a link failure contributes directly to this inhibiting traffic. Various attempts to facilitate route discovery and to address this problem are found in numerous routing protocols. Protocols such as Dynamic Source Routing (DSR), Ad Hoc On-Demand Distance Vector (AODV), and Optimized Link State Routing (OLSR) are several examples [4]. The attempts to maintain a route in the event of a link failure increase the amount of inner node communication. Since one of the problems with MANET communication is network congestion, a first step towards formation flight can be made through improved inner node communication.

The remainder of this paper is organized as follows. A background of state-of-the-art routing protocols, cluster formation, and attempts that have been made to alleviate the network communication congestion problems is reviewed. The methods to address these problems, including assumptions, requirements, and limitations specific to the Network Simulator NS-2 are given [5]. The simulation results and analysis are detailed. Finally, future efforts and conclusions are presented.

2. BACKGROUND

There are many protocols that have been developed and studied in an effort to alleviate network congestion in MANET environments. Some examples include DSR, OSLR, and AODV. A summary of these protocols and their attributes are given below.

DSR is an on demand source routing protocol. The routes are formed only when needed and the message packet headers contain the entire route path. The state of the link is verified on a per hop basis, so control packets are not required. The available source routes are stored in a local route cache to reduce the frequency of route discovery. Route error packets are sent when a node is unable to forward a packet to the requested next hop. In simulations, DSR has shown to perform well in situations of few nodes and low mobility. Under these conditions DSR does well because of the low route discovery maintenance overhead. However, when there are a large number of nodes and high mobility, the size of the message header that contains the ID of the nodes within the routing path becomes large and storage on the source node can become cumbersome. In a highly mobile network, such as UAV in formation flight, the need to discover and maintain routes is of primary concern [4].

OSLR is a modification of link state routing protocol [4] designed to make it more suitable for mobile ad hoc network communication. The protocol maintains routes with a partial state table made up of a subset of the neighbors. These tables are updated by sending periodic hello packets to each of the neighbors. The subset of the link states are not constricted by the shortest route which helps decrease the amount of communications required. Each link state has an expiration time associated with it, when a link expires it is deleted from the state table. The modified state table and lack of shortest route requirements make OSLR a more efficient ad hoc network protocol. However, in a highly mobile network the need to send hello messages and update the state tables is costly. In a large network, these tables can become quite large and computationally intensive.

AODV is an on demand source routing protocol. It determines a route only when one is needed and if a previous one is not available. AODV uses three message types to determine a route. The RREQ is a request for a route, RREP message is a route reply, and the RERR message reports an error to a route. The local nodes maintain a one hop neighbor table that is used to form the path to the destination. Destination and source sequence numbers are used to ensure a fresh route. Network congestion is an issue with AODV during the route determination phases. In a highly mobile network, this congestion increases due to the need to refresh the routes more frequently.

All of these protocols provide a reasonable solution for a mobile ad hoc network when the nodes exhibit low mobility. However, when the nodes in the network move at a high rate of speed such as in an UAV and in addition are peer aware, as in formation flight, the inner node communication increases network congestion. The ultimate result is an increase in data packet losses. A common solution to this problem is to limit the number of nodes in a cluster or flight formation, which has the effect of limiting the number utility of nodes in the MANET formation.

In an effort to expand the potential network size, the concept of sub clusters is studied by [2] and [3]. The network size can be expanded through gateways between clusters of nodes. This allows each sub cluster to communicate with others in the network. The capacity of each sub cluster is limited by the network congestion, but the ability to enlarge the number of nodes in the entire network is limited in large part, by the intra cluster communication needs. The issue to be studied here is the introduction of a timing mechanism that is capable of decreases the network congestion in order to maintain the network topology and achieve a reliable formation flight. Determining a bound on the size of the sub-clusters served as a first step in developing a network of sub-clusters. The capacity of clusters within a MANET and identifying a bound on that capacity has been studied extensively. [6] – [9] have all analyzed and identified bounds on the capacity of wireless networks.

3. METHOD

A hybrid protocol is developed to decrease the inner node communication (communication between nodes) and limit the number of collisions that occur during the route seeking process. This protocol is based on the AODV protocol because it has been shown to have a lower packet delay in stressed networks [12]. The method incorporates a time component to the AODV protocol, similar to that of the Slotted ALOHA protocol [10, 11]. The method sets aside a particular time-slot for one communication node (or UVS node) to communicate data to the master node or cluster head. Each node is given communication privileges over all other nodes in the assigned time-slot.

A MANET is limited by network capacity and its high cost in maintaining communication routes. Formation flight of a MANET network, requires the nodes to be aware of the other nodes for coordination purposes. This peer-to-peer interaction results in increasing the communication between the nodes and further limits the capacity of the MANET resources [6,7,8]. In particular, a large part of the MANET's network congestion is due to the process of route discovery. Wired network protocols such as TCP, sense the congestion of the network and dynamically change the buffer size of the message to be sent and a time-out window size that controls the re-sending of an unsuccessful send. In a wireless network, knowledge of network congestion, lost data packets, and link-failures are difficult to determine and to distinguish. For these reasons, a more deterministic approach is considered that anticipates the reduction in network capacity. In the approach suggested in this paper, the UVS node communication is performed in a controlled, collision-free routing protocol. The new protocol is a hybrid implementation of AODV that introduces a communication time-slot that restricts node communication during each time-slot period (τ). The time-slotted inner node communication mechanism acts to throttle the network usage and decrease network congestion in support of formation flight traffic coordination.

In a non-ideal, single hop network between the source and destination, multiple hops between intermediate nodes are typically required for route discovery and data transmission. Time-slots, allow neighboring nodes to transmit data in a collision-free manner and minimizes the number of dropped message packets due to collisions. Although this method does reduce the useable network bandwidth and the overall network traffic for the routing protocol it does increase system scalability. The loss of data packets that contain navigational information may have a serious effect of the ability to maintain the formation. For this reason, bandwidth is traded for a higher percentage of successfully delivered packets.

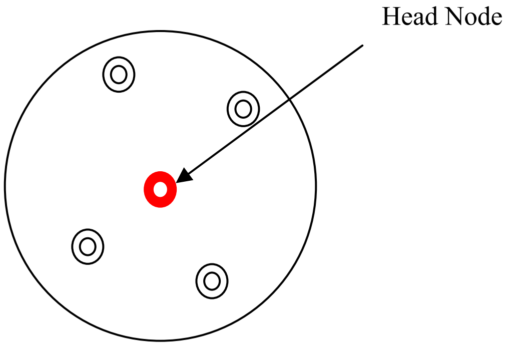

Figure 1: Star cluster network topology

Thus the introduction of communication transmission time-slots provides a mechanism for collision-free data transfer between cluster nodes and the cluster head. As an example, the head node could transmit in the even time-slots while the other nodes transmit during the odd numbered time-slots. A second graduated approach could divide the time-slots among all nodes. This division of time slots could range from any node communicating at any time to each node having a uniquely assigned time-slot. The case where any node can transmit at any time is the standard AODV protocol implementation. In this study it will be assumed that the head node transmits only during the even time slots while the graduated approach is left as future work.

Assuming the communication time is broken into time-slots of length τ and the slots are numbered $t = 0, 1, 2 \ldots T$; where s_t is the communication time at slot t and $s_T = T^*\tau$ is the total communication time. The head node is assigned all even time-slots and can transmit messages only during those times. All other nodes are assigned odd numbered time-slots one per node. The head node will initiate a route discovery in slot 0 and send a message to the first node in the network. In time-slot 1, that node will respond using the return route found in time-slot 0.

This time-slotted routing protocol is tested using the NS2 (V2.29) simulation environment. The AODV protocol in the NS2 simulator is modified and the simulation parameters tested using the new time-slotted approach. The simulations are performed assuming no movement of the nodes in a simplified network to provide a baseline for more complex scenarios. These results are compared with more complex network topologies and movements using the NS2 propagation shadowing model and a spring mobility model (SMM) developed by Webber and Hiromoto [6].

Figure 1 illustrates the network topology of a small cluster. It is initially defined as a simple star network. All traffic is routed though the head node. The source is not more than one hop from the destination. Webber and Hiromoto [6] identified an upper bound on the number of nodes that can join a network using the AODV protocol and a shadowing propagation model. They determined the number of nodes that could be added to a network and still maintain communication at a level of 50% dropped packet rate. Based on these results, the number of nodes in the network studied here is varied between 2 and 19.

In order to understand the behavior and performance of the time-slotted cluster head approach, the following metrics are measured.

- Total packet traffic, including payload and routing
- Payload packet traffic
- Packet delay

This traffic was monitored at the node, Media Access Control (MAC), and the interface queue levels. NS2 provides four different tracing options for tracking packets. The agent trace gives packets at a node level. The router trace reports the packets that pass through the node routers. The Media Access Control (MAC) trace reports all packets through the MAC layer of the network communication. The Full Interface Queue (IFQ) trace gives reports of all full interface queues throughout the transmission.

In order to monitor the identified metrics, all available routing and data packet traces in NS2 are enabled. The agent and router traces provide a reasonable view of the traffic of the total network, however, the use of AODV places a significant burden on the MAC layer. For this reason, the activities of the MAC layer are also traced. In particular, the AODV protocol sends requests and replies in order to identify a route. Each of these request and reply messages generate an additional four MAC level sends and four MAC level receives. In a network with 19 nodes, four MAC messages are required between the source and the destination node. This is a minimum of 72 messages to generate routes between all 19 nodes. This does not account for the messages sent from the head node to the other 18 nodes. This does not account for the RREQ messages generated by the other 18 nodes in order to assist the head node in determining the desired route. There is also MAC layer traffic required to send the payload bearing packets. Thus without an AODV throttling mechanism, the increase in MAC traffic increases the burden on the MAC level and results in MAC layer collisions and increased dropped packets.

The UAV group is part of the National & Homeland Security Directorate at the Idaho National Laboratory (INL) which provides wireless testing solutions for government critical missions. The following assumptions are based on their requirements and are used for the simulations.

a) A 95% successful packet delivery rate with a data rate of 1 Mbps for payload packets of size 512 bytes is assumed for positive real time control.

b) All UAV have an on board Global Positioning System (GPS). The time-slotted approach requires a mechanism for synchronizing the UAV clocks to ensure that all nodes synchronized. The GPS clock is used for this purpose. The GPS refresh rate is 1 Hz and; therefore, our transmit model and slot size will include allowance for any potential clock skew (drift) that might occur. It is also worth mention that the transmission time for dynamic flight planning is a transient requirement and it is of a bursty nature. If a flight path were altered the impact would be intermittent on the network. The communication needed to maintain peer-to-peer node position within the formation is a continual requirement and places a continual burden on the network.

To implement a time-slotted protocol, the time-slots must be large enough to support the aggregate of all routing packets so that $C = \Sigma$ size(RREP, RREQ, RERR, Data) for all messages required in both the route discovery and the payload or data transmission process. The messages can be sent in the first instance of the time-slot, similar to the Slotted ALOHA protocol [10]. A start-window for the sending of packets by a node can be created using a random send time in each slot. The ALOHA protocol refers to this window as the back off period, for consistency, the same notation is used here. The back off period can also be adjusted to study the network performance under instantaneous or delayed send requirements. The time-slot is defined to be

$\tau = C*D + \rho + B$

Where

B = back off period
C = largest control packet length
D = data rate
ρ = maximum skew, clock drift
T = total number of time-slots
t = current time-slot {0, 1, …, T}
s_t = simulation time at time slot t = 0, 1, …, T
s_T = total simulation time
τ = time-slot size

To maximize network bandwidth usage, the value of τ must be as small as possible while still allowing time for route discovery and payload traffic transmission to occur. The choice of a minimum value of τ must provide for a reasonably maximum clock skew. The determination of this clock skew time is based upon the following observations. Each UAV has an onboard GPS that is refreshed once a second. The manufacturer quoted skew for that clock is 5×10^{-4} ms. The manufacturer quoted clock skew for the processor clock is 50 parts per million (5×10^{-2} ms). The temperature at higher elevations is colder and the temperature differential will cause variation in the GPS hardware. The temperature change is assumed to be in the range of 25 degrees, so the resulting error and latency due to temperature is .5 ms. Assuming a dedicated one pulse per second interrupt allows the GPS pulse can update the processor clock every second with a delay of 2×10^{-2}, and; thus, the maximum clock skew is .5705 ms. Allowing for the clocks to skew in a positive or negative direction results in $\rho = 1.141$ ms.

The network topology is a factor in determining a value for C is the network topology. When using the star network as in Figure 1, the head node broadcasts a RREQ that identifies a destination node. All nodes that are within the radio range receive the RREQ. For this topology, the destination node receives the RREQ and generates an RREP. All other nodes that are out of range of the destination node will not receive the RREP and will create an RREQ in order to assist the head node in discovering a route to the destination. Assuming the star topology is uniform and all nodes are at a maximum communication distance from the head node, for networks with 6 nodes or greater, the head node will send and receive RREQ messages in four different route discovery attempts before all nodes in the network stop trying to find the requested route. This is in addition to processing the RREP from the destination node. If a route discovery process completes with no drops there will be an average of an additional 24 MAC messages sent and received by the head node.

3.1. Theorem 1

Four is an upper bound on the number of RREQ messages required in a single hop network with the star topology described in Figure 1 to make all nodes aware of route discovery completion.

Let

R_i = the communication range of node i $\forall$ i = 0 … n-1
n = number of nodes
n_0 = head node
r = effective radius of transmission
ε_i = set of effected nodes by a transmission from node i $\forall$ i = 0… n-1
N = $\{n_i \mid i = 0\ldots n\text{-}1\}$

Assume the star network configuration depicted in Figure 1 such that $N \subset \varepsilon_0$
n_i $\forall$ i = 0 … n-1 are uniformly distributed over the network.
The distance between n_0 and all other nodes is r.

Referring to Figure 2 and using

A_{ol} = area of overlap between node 0 and any other node in the network
A_{tri} = area of one of the four triangles in the diamond that lies inside the overlapping communication area.
A_{sec} = area of a sector in a circle
Θ = angle of the sector in a circle

The area of the overlap between node 0 and any other node in the network can be calculated as follows.

$$\mathrm{A}_{\mathrm{tri}} = \frac{1}{2} base * height = \frac{1}{2}\left(\frac{1}{2}r\right)\sqrt{r^2 - \frac{1}{4}r^2} = \frac{\sqrt{3}}{8}r^2$$

$$A_{\sec} = \frac{1}{2}r^2\Theta = \frac{1}{2}r^2\frac{2\pi}{3} = \frac{\pi}{3}r^2$$

$$A_{ol} = 2A_{\sec} - 4A_{tri} = \frac{2\pi}{3}r^2 - 4\frac{\sqrt{3}}{8}r^2 = \frac{4\pi - 3\sqrt{3}}{6}r^2$$

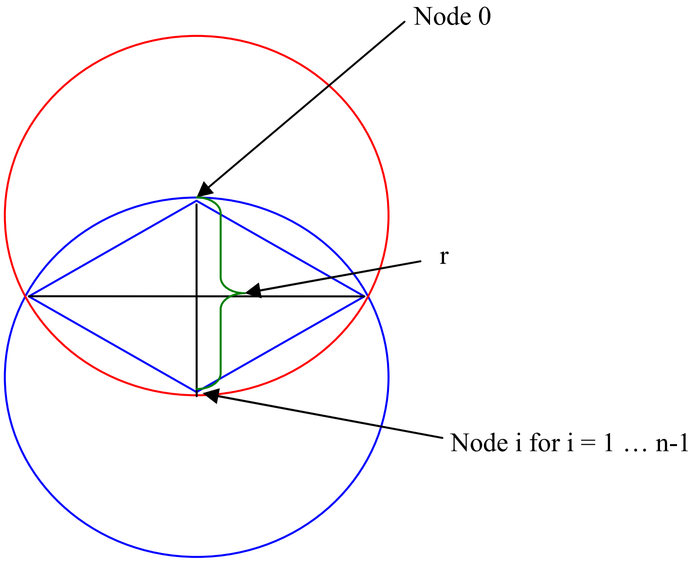

Figure 2: Diagram of area of overlapping communication between two nodes in the star network topology

Such that the percent of overlap in a nodes communication range would be

$$\frac{A_{ol}}{A_{circle}} = \frac{\frac{4\pi - 3\sqrt{3}}{6} r^2}{\pi r^2} = \frac{4\pi - 3\sqrt{3}}{6\pi} \approx 39\%$$

$\Rightarrow$ At most 39% of $N \subset \varepsilon_i \; \forall \; i = 1 \ldots n\text{-}1$ receive the first RREQ

$\Rightarrow$ Another RREQ can reach at most 39% of the nodes in the network

$\Rightarrow$ Two more RREQ messages could be sent if any two of the remaining 22% of the nodes are greater than r distance apart.

$\therefore$ It takes at most 4 RREQ message forwards to occur for all nodes in the network to know a route has been discovered.

3.2. Corollary 1

When there are less than 6 nodes in the network four or less RREQ message forwards are required for all nodes in the network to know a route has been discovered.

Assuming a uniform star topology with maximum communication distance between the head node and all other nodes, in order to show a six node network is the smallest number of nodes needed to reach the bound shown in Theorem 1 each network of size less than six is considered.

In a network with 2 nodes, there is only one route and only one RREQ to be issued.

In a network with 3 nodes that is uniformly distributed with maximum communication distance between the head node and all other nodes, 2 of the nodes are not in communication range of each other.

$\Rightarrow$ Two RREQ's will be sent to the head node and all will know the routes have been discovered.

In a network with 4 nodes that is uniformly distributed with maximum communication distance between the head node and all other nodes, 3 of the nodes are out of communication range of the other non-head nodes. A 39% communication range overlapped between each node and the head node corresponds to an angle of $2\pi/3$ and each node would be distributed in the star network at an angle of $2\pi/3$.

$\Rightarrow$ Each node will submit an RREQ for a maximum of three times to complete the routing task.

Similarly, in a network with 5 nodes that is uniformly distributed with maximum communication distance between the head node and all other nodes, 4 nodes are distributed at a 90 degree angle and out of each others communication range.

$\Rightarrow$ Each node will submit an RREQ for a maximum of four to complete the routing task.

$\therefore$ For uniformly distributed networks using a star topology with less than 6 nodes; four or less RREQ message forwards are required to complete the route discovery process.

3.3. Application of Theorem and Corollary (Lower Bound)

The lower bound on τ in a uniform star topology with at least 6 nodes is 9.43 ms.

Assume there is maximum communication distance between the head node and all others in the network. Further assume a 512 byte packet size with header information resulting in 600 byte packets, a MAC level packet and header size of 56 bytes, and a data rate of 11 Mbps. It would take 600*8/(11*1000) = .436 ms to send a 512 byte packet and 56*8/(11*1000) = .0409 ms to send the MAC level packets.

It takes .0409 ms * 8 MAC level packets = .3272 ms to find a route with no other nodes or network traffic involved. Corollary 1 and Theorem 1 show for networks with 6 nodes or greater, the head node will send and receive RREQ messages in four different route discovery attempts before all nodes in the network stop trying to find the requested route. So the maximum time to find a route for 6 or more nodes is 6*4*.3272. Using $\rho = 1.141$ ms for the clock skew, and a back off period of zero results in $\tau > 9.43$ ms. The results in section 4 are obtained using $\tau = 14$ ms, which is a larger than necessary slot time to provide for route discovery and payload packet transmission while still supporting the necessary 1 Mbps successful delivery rate.

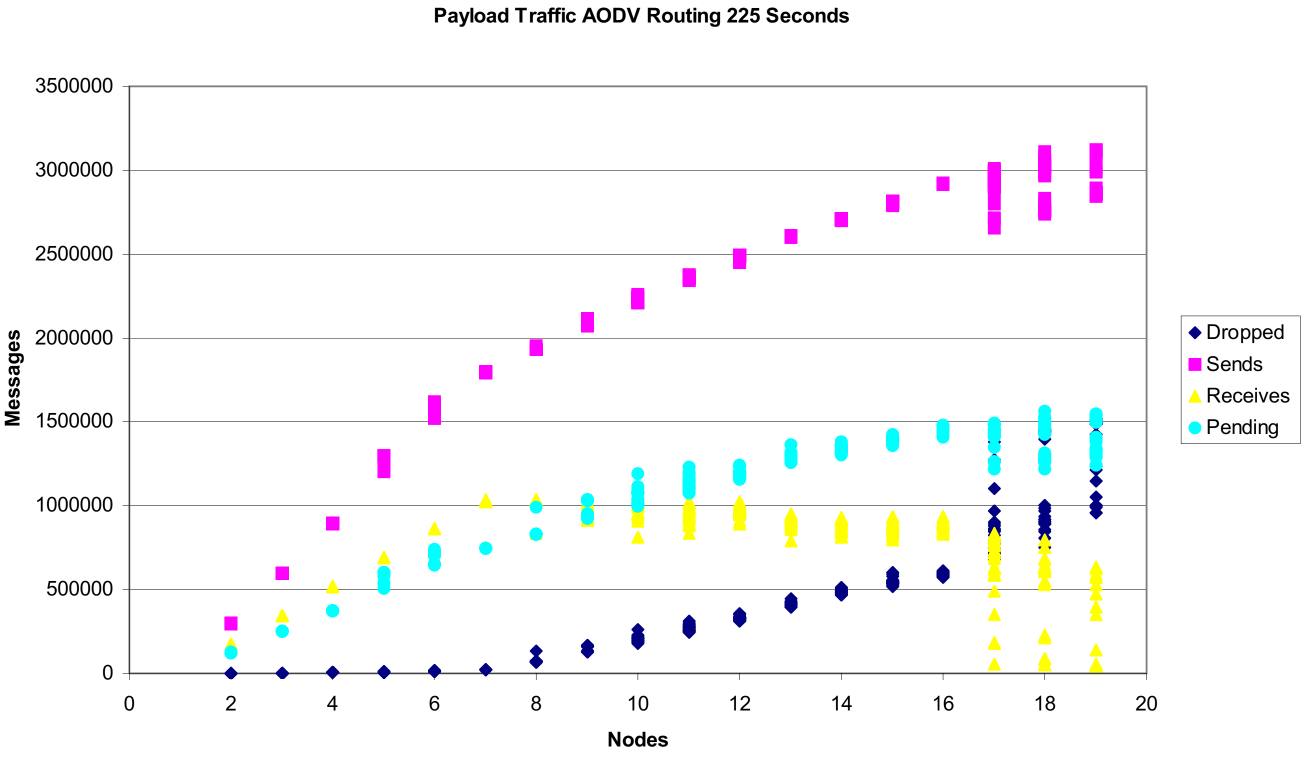

Figure 3: Standard AODV $s_T = 225$ second.

4. RESULTS

The simulation results are based on the scenarios implemented by Webber and Hiromoto. The star network and spring mobility model are used as a baseline for comparison with the time-slotted protocol results. The configuration is changed in order to decrease the acceptable packet loss to 5% from the previous level of 50%. In order to compare the original AODV protocol with the time-slotted version, the network is simulated without movement and subsequently with movement. The results presented in this section are for the mobile network, as the goal is to support formations of nodes in motion.

4.1. Mobile Network

The mobile network is simulated using the original AODV protocol and the proposed time-slotted protocol. The spring mobility model is used to simulate the movement of the nodes. The movement is tracked at 2, 4, 7, and 8 second durations and through course deflection angles from the true direction of 0, 5, 10, 15, 20, 25, and 30 degrees.

Figure 3 shows the distribution of data or payload carrying message that occur when the nodes in motion are routed using standard AODV routing over a 225 second simulation time. The results for all rotation angles and all time durations are shown on the same plot. The general trend of the traffic can be seen with a larger deviation occurring in the cases with 17, 18, and 19 nodes. It is worth noting that Webber and Hiromoto found a marked decline in the network performance after 16 nodes are added to the cluster. Our results support this upper bound on the capacity of an AODV MANET with this topology. The results also show that AODV is able to maintain a greater than 1 Mbps data rate but when 8 nodes or more are added to the network the drop rate exceeds the 5% required in order to maintain UAV formation.

Figure 4 shows the resulting payload message distribution when a 14 ms time-slot is used in a 225 second simulation. The time slot is implemented for both route finding and payload traffic because it simplified the implementation. The use of the time-slot decreases the capacity of the network and causes the results to be more pessimistic. The maximum drop rate is .966% with the average being .0185% over all node combinations, while still maintaining payload traffic receive data rate of 1.02 Mbps. The variances are due to the randomness caused by the spring mobility model and the shadow propagation models used to simulate the node mobility and the wireless communication effects. For example, the maximum number of dropped messages occurs when there are five nodes in the network. This is due to a node moving beyond the signal boundary and loosing a communication route. While the increase in drop rate appears to be rather large, it is important to note that the actual drop rate is still less than 1% and the received packets remain at a consistent level. Since the transmitted messages are sending are intended to support and maintain formation flight having consistent and reliable communications is highly desirable.

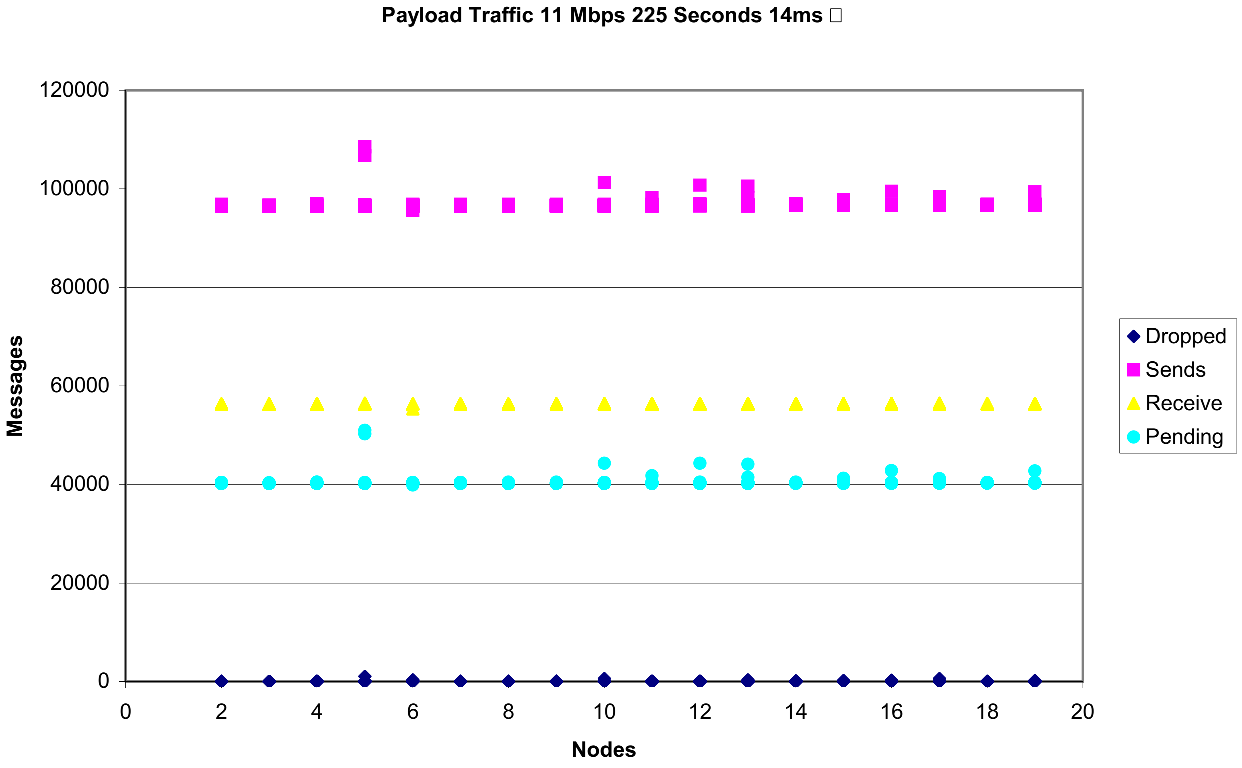

Figure 4: $\tau = 14$ ms $s_T = 225$ second

The average drop to send ratios for both the AODV and time-slotted protocols are shown in the table below. When there are less than 8 nodes in an AODV managed network the ratio is below the 5% accepted rate, however, the ratios for the time-slot managed network are better than the AODV in all but the 2 node case. While the total network traffic decreases, the time-slotted method provides a consistent level of reliability and scalability over a broader range of network sizes. It should also be noted that the frequency of conversation for individual nodes is inversely proportional to the number of nodes in the network.

AODV				Time-Slotted Protocol			
# Nodes	Sends	Drops	%Drop/Send	# Nodes	Sends	Drops	%Drop/Send
2	297620	79	0.026544	2	96823	41	0.042345
3	595320	1360	0.228449	3	96561	14	0.014499
4	895124	3180	0.355258	4	96608	17	0.017597
5	1287130	6845	0.531803	5	96764	14	0.014468
6	1572299	13197	0.839344	6	95600	352	0.368201
7	1792147	20828	1.162181	7	96579	12	0.012425
8	1928818	133854	6.939691	8	96634	13	0.013453
9	2110803	161612	7.656423	9	96760	36	0.037205
10	2235464	201646	9.02032	10	96811	563	0.581545
11	2368918	291292	12.29642	11	96849	47	0.048529
12	2486714	313690	12.61464	12	96712	23	0.023782
13	2600369	442459	17.01524	13	98160	331	0.337205
14	2702066	489896	18.13042	14	96771	24	0.024801
15	2811593	534245	19.00151	15	97840	35	0.035773
16	2915644	586655	20.12094	16	99524	39	0.039187
17	2913889	847099	29.07108	17	98347	23	0.023387
18	2980088	969730	32.54031	18	96750	22	0.022739
19	2988413	1144348	38.29283	19	99403	34	0.034204

5. Future Efforts

The results presented in this paper suggest several additional approaches in enhancing the use of the time-slot method. For example, the duration of the time-slot is selected to be large enough to accommodate the route discovery process when it occurs. A more robust approach would be to design an intelligent time-slot protocol that adjusts its time-slot window when a link-failure is detected and the route discovery process is required or requested. The interception of RREQ and RERR packets can trigger the adjustment of the time-slot window in a fashion similar to TCP. This self-adjusting time-slot window would effectively increase the payload traffic through the network. Another variation is to make the time-slot window size dynamic. A variable time-slot would allow for the clock skew to increase over time and avoid the use of one large time-slot that is as big as the largest expected drift. This approach would allow the time-slots to gradually enlarge until the clocks on the nodes are synchronized again. This modification seems beneficial since the time skew is twice as large as the required time to transmit a 512 byte packet. Allocating the time-slots based on message type rather than node could also prove to be useful. When using the star network topology and allocating the head node the even time-slots, the head node performs most of the route discovery. Allocating time-slots based on message type would cause the head node to have a 9.752 ms time-slot and the rest of the nodes to have a 1.577 ms time-slot. This would provide an alternate way to allow a large enough time-slot for the routing protocol while minimizing unused bandwidth during payload transmission. An additional alteration to the method presented here is to relax the time-slot node allocation constraint and allow more than one node in the network to transmit during each time-slot. Finally, an implementation using the time-slot method for just the routing protocol would increase the potential overall network traffic.

These results are based solely on simulations using the NS2 simulator. For a more realistic approach, the next step is to include a commercial off the shelf (COTs) autopilot software simulator that drives the NS2 simulator. The integration of this software would form a closed loop simulation that would more closely represent the movement of the nodes to that of the actual UAVs. The ultimate goal is the replacement of the software simulator with an actual UAV autopilot creating a simulation with hardware in the loop; taking us one step closer to formation flight. It is anticipated that the resulting hardware in the loop simulation will result in a more realistic model.

6. Conclusions

The use of time-slot allocation to coordinate communication between nodes in a Mobile Ad hoc Network is shown to enhance and improve the Quality of Service (QoS) of node communication by minimizing data packet drops. Adjusting the time-slot duration to be large enough to facilitate the transfer of the largest packet and routing message requirements while avoiding data packet collisions maximizes the reliability of the communication. While the number of messages that can be sent is decreased by this method, and results in a lower data transfer rate, the communication throughput sustained by the time-slotted routing protocol is sufficient to maintain formation flight. The important results to note are the reliability of the communication, the scalability of the nodes in the formation; and the hazards of a dropped navigation packet that may potentially disrupt or alter the mission beyond recovery.

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