Trajectory-aware Ad hoc Routing Protocol for Micro Aerial Vehicle Networks

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ABSTRACT

Micro Aerial Vehicles (MAVs) are small unmanned aerial vehicles (UAVs) that are generally equipped with camera, GPS and other sensors and are envisioned for many civil and commercial applications. Some of these applications require transmitting multimedia traffic and demand for a high wireless network throughput. In this paper, we consider an application scenario where a team of MAVs cover multiple areas of interest; e.g., during sports events, following known trajectories (mobility paths) and transmitting continuous streams of sensed traffic (images or video) to a ground station. We propose a Route Switching (RS) algorithm that utilizes both the location and the trajectory information of the MAVs to schedule and update routes to seamlessly transmit traffic to the destination. Simulation results show improved network performance in terms of throughput in comparison to Ad-hoc On demand Distance Vector (AODV) and Location Aided Routing (LAR) since the proposed algorithm exploits the added path information for route discovery.

1 INTRODUCTION

Numerous applications on aerial mapping, search and rescue, surveillance, transportation, etc. are identified [1, 2, 3, 4, 5, 6] where MAVs can be used with reduced cost and minimal infrastructure. Multiple MAVs can perform tasks faster and efficiently through coordination but would require strong wireless networking and communication capabilities in three-dimensional space [7]. In addition, Quality of Service (QoS) requirements are to be met to support these applications. The question arises if the existing widely accepted routing algorithms are sufficient to fulfill the requirements for a mission oriented network of MAVs [8].

In this paper, we consider a network of MAVs, where each MAV is equipped with Global Positioning System (GPS) and 802.11a wireless transceiver and is continuously streaming traffic to a ground station while following a pre-defined path in three-dimensional space. We propose a scheme that schedules routing by exploiting the location and trajectory information of MAVs participating in the mission to improve the overall network performance. We investigate the network performance in terms of achieved throughput to evaluate the behavior of existing routing protocols namely AODV and LAR in a mission scenario and analyze if a simple route switching scheme can help in achieving better network performance and provide better support to fulfill QoS requirements of MAV applications.

The remainder of the paper is organized as follows. In Section II background on existing routing protocols namely AODV, LAR and Greedy Parameter Stateless Routing (GPSR) is summarized. Proposed route switching algorithm is presented in Section III. Section IV discusses the simulation setup and results and Section V concludes the paper.

2 RELATED WORK

A network of MAVs is associated with certain other constraints concerning routing compared to a ground wireless network such as high mobility, frequent topology changes, and routing in 3D space. AODV [9], LAR [10], Dynamic Source Routing (DSR) [11] and GPSR [12] are all reactive ad hoc routing protocols that require repetitive and exhaustive route discovery when a source tries to find a route to the destination. AODV broadcasts route request packets in the network to find the path to the destination. When an intermediate node receives a route request, it broadcasts the route request to its neighbors to find a valid route to the destination. Upon arrival of a route request at the destination node, the node sends a route reply using the reverse path. This way a route from source to destination is established.

LAR improves the flooding based route discovery mechanism by using the location information e.g. through GPS along with the flooding based scheme for route discovery. Source sends route request packet in the direction of the expected zone of the destination based on the location information. This directed broadcast reduces the number of packets required for route discovery and improves the overall network performance in terms of achieved throughput.

GPSR uses geographical location of the destination to route packets. Beacon signals are used for this purpose, which propagate location information of the nodes in the network. A source sends data to the destination by forwarding packets to its closest neighbor that is also closest to the destination, called the greedy forwarding mode. If the data packet

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reaches a region where greedy forwarding mode is not possible, the source node may shift to the perimeter forwarding mode to forward the data using planner graph traversal. A node using perimeter forwarding mode would shift back to the greedy forwarding mode whenever possible. Combining the greedy forwarding mode and the perimeter forwarding modes give the full GPSR algorithm.

In a multi-MAV environment the network topology changes frequently due to high mobility. The above mentioned protocols are not designed for such a setup [8] since the change in the network topology may lead to route disconnection from source to destination as the relay nodes no longer remain in the radio range. Subsequently, a route error message is sent to the source which then broadcasts a new route discovery message to find the new route to the destination. This consumes additional network bandwidth along with the delay in the traffic from the source to the destination. In this paper we propose a route switching scheme, explained in the next section that exploits the location and trajectory information to schedule routes from source to destination. In other words the route from the source to destination is calculated before the source loses its route to the destination due to a change in the network topology.

3 Route Switching

A trajectory-aware route switching mechanism is proposed to overcome the route error and the route discovery overhead of existing ad hoc routing protocols. The idea is to maintain information about the available routes from source to destination and switch to an alternate route when it is likely that the current route is going to break. We utilize prior knowledge on the position and mobility of nodes participating in the mission to switch to an alternate route.

The MAVs participating in the mission might need multiple hops to transmit their multimedia traffic to the destination. Since all MAVs are mobile, the established route being used to route packets to the destination may get disconnected. When this happens AODV or LAR will send a route error message to the source to which the source will initiate a new route request. However, using the prior knowledge of path information it can be predicted when a next hop MAV is going to go out of the communication range of an MAV that is part of the communication route from source to destination.

In such a case, the time for route error and thereafter a new route discovery can be avoided by switching to an alternate intermediate MAV before the current next-hop MAV goes out of the communication range. This is further illustrated in Fig. 1 where M_S is the source MAV, M_D is the destination ground node, M_{R1} and M_{R2} are potential MAVs that can relay from source to destination and M_N are other source neighboring MAVs. Here at time $T_{\alpha-1}$ route from source to destination is established via M_{R1}. We know that at time T_α, M_{R1} would no longer be in M_S radio range. Therefore, before time T_α the route from M_S to M_D can be switched via

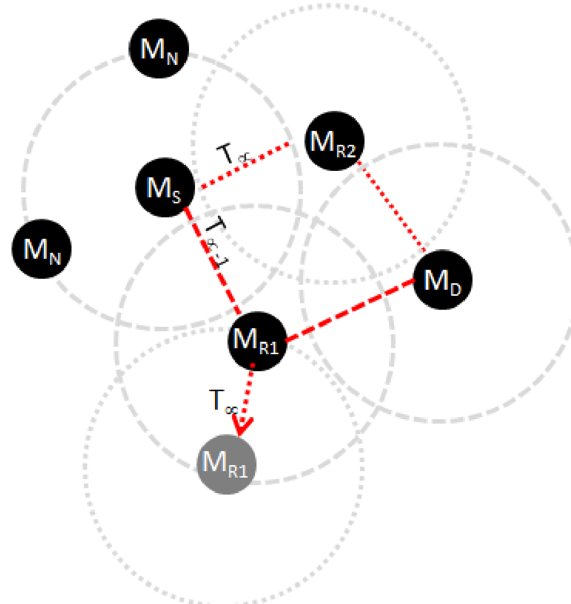

Figure 1: Transmission range and routes. The dashed and dotted circles and lines are the current and next transmission range and route respectively.

M_{R2} to avoid the time required for a new route discovery. In other words a new route can be established using the neighbor, location, trajectory and time information. This way the time for a new route discovery can be minimized as the communication link between M_S and M_D will remain established as long as an alternate neighbor M_{Ri} to relay is available.

3.1 Assumptions

1. Destination node is stationary on ground, all other nodes are moving in three-dimensional space.

2. The duration of the mission is defined and is known in advance to all nodes in the network.

3. In mission-oriented networks, where the team of MAVs operate together to achieve a goal, e.g., to continuously cover a known area, optimum pre-defined paths can be used [13]. Therefore, we assume that at any time instant of the mission, the source knows the location and trajectory of any node in the network through predefined path information.

3.2 Trajectory-aware routing protocol

The proposed routing-protocol is summarized in Algorithm 1. To find the route from the source to the destination, each source node first gains knowledge of its multi-hop neighbor nodes. The source then locates the destination node to find out if it can directly connect to the destination at any time instant during the mission. This is done using the trajectory information of the source and the destination. If so, the source directly connects to the destination to transmit its data whenever possible and seeks the help of relay nodes otherwise. If a direct connectivity is not possible i.e., the destination is out of source communication range a multi-hop path has to be established. To do so, the source looks for its n^{th} hop neighbors that are connected to the destination. The n^{th} hop neighbors are sorted based on connectivity time with the destination. Now to select the n^{th} hop neighbor, the algorithm finds the $(n-1)^{th}$ hop neighbors that are connected with n^{th} hop neighbors and so on until $(n-m)^{th}$ hop is the source itself. The connectivity time of all intermediate relay nodes is sorted. The calculated route is the one that provides the maximum connectivity time from the source to the destination. In other words, multiple routes are calculated but the route that has the maximum connectivity time is selected. However, since the source nodes are mobile, the calculated route can disconnect and so a new route must be calculated before the source experiences a disconnection. The algorithm thus calculates a new route as many times a disconnection is expected.

Algorithm 1 Trajectory-aware routing protocol

Input parameters: node trajectory and timing information, transmission range, channel model, source location.

1. Source acquires knowledge of its multi-hop neighbors
2. Source checks if it will directly connect to the destination at any time instant during the mission
3. Source routes its packets to destination directly whenever connected
4. Otherwise, finds the n^{th} hop source neighbors that are connected to destination
5. Sort connectivity time of the n^{th} hop neighbor with the destination and the $(n-1)^{th}$ hop neighbor, select the most connected one
6. Decrement n and repeat steps 4 - 6 until route is found
7. Send packets to destination through the calculated route

There are some expected pros and cons involved. The proposed scheme benefits by providing an alternate route from the source to the destination during the mission; i.e., when a moving relay node gets out of the communication range of the source an alternate route without a new route discovery can be established to maintain connectivity. In other words, considering our mission, the expected delay in the multimedia transmission can be reduced through this scheme since the route error and route discovery overhead is avoided.

Nevertheless, it also comes with a cost of maintaining the knowledge of alternate routes. Routes are calculated based on the trajectories of the MAVs participating in the mission. The computation can be done centrally at the base station, which can then send the route information to each MAV or in a distributed way, where each MAV maintains trajectory information of all the nodes in the network and calculates its own route accordingly. In either way, some storage capacity is required to maintain the trajectory information of the MAVs. The storage requirement can increase if the mission time is extended or more MAVs are added to participate in the mission.

Also, the computational cost to check when a relay node is going to get out of the range and when to shift to an alternate route is involved. More computational power is required to compute the routes as the network size increases or as the number of hops from the source to destination increase or both.

4 Results and Discussion

Unless otherwise stated, the parameters used in the simulations are given in Table 1. These parameters are chosen in accordance with our platforms and experimental work [14]. We used Omnet++ as our simulation platform. Number of source MAVs chosen in the network are 1, 3, 6 and 9 respectively. Each source MAV continuously sends UDP traffic to the ground station at a rate of 54 Mbps such that the maximum channel capacity is utilized. The UDP packet size is set to 1480 bytes.

We investigate the performance of the proposed protocol for two mobility scenarios. First, we consider random mobility scenario where each node initially places itself randomly over the constrained area. Nodes then choose their destination randomly with random speed and direction. We then consider trajectories from a real coverage mission scenario of a disaster rescue operation [15]. The scenario considered in this paper is to provide live coverage through multimedia streams to multiple areas of interest where some sports events e.g., a marathon or a cycle race are taking place.

4.1 Random mobility scenario

First scenario uses random mobility model for hosts carrying camera, GPS, other sensors, etc. Random mobility model is popular due to its simplicity. To simulate the scenario we generated random trajectories shown in Fig. 2. We consider these generated trajectories as the area of interest for the MAVs to follow and transmit traffic to the ground station. Using this model a mobile host changes its direction uniformly randomly between $0° - 360°$, speed from 2 mps $-$ 5 mps after a random interval of 5 s $-$ 10 s. The destination node (FixedHost) denoted by ★ is kept stationary and all other nodes transmit while they are moving. Nodes move without any pause at any location. Three stationary relay nodes denoted by ♦ are also placed randomly to help route the traffic to the destination node. Stationary nodes are important since without them some source nodes e.g., MAV0, MAV6 and MAV8 are unable to form a route to the destination at many time instances during the mission time. Mobility of MAVs is constrained to an area of 1000 m $\times$ 1000 m $\times$ 50 m.

Table 1: Simulation parameters

Parameters	**Values**
Radio Interface	802.11a
Carrier Frequency	5 GHz
Number of Channels	1
Bit Rate	54 Mbps
Rate Adaptation	Adaptive Auto Rate Fallback
Mode	Ad-hoc
Channel Propagation	Free Space, Rayleigh
Transmission Power	7 dBm
Thermal Noise	-95 dBm
Radio Sensitivity	-90 dBm
Path Loss Alpha	2
Area bound	1000 m x 1000 m x 50 m
Simulation Time	900 s

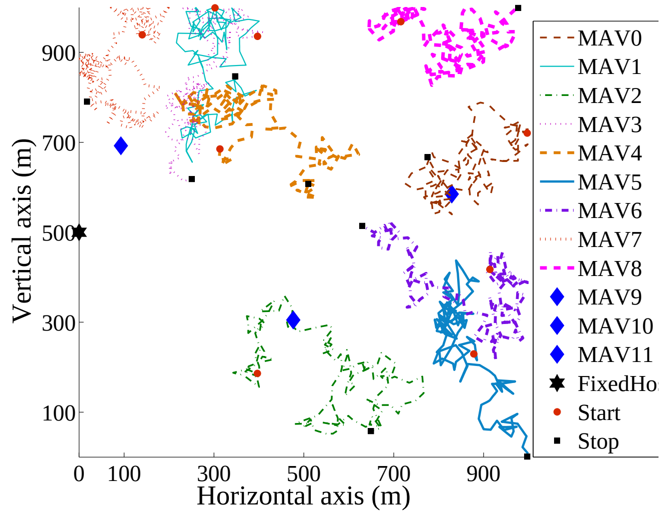

Figure 2: Trajectories: MAVs follow random paths

We calculate achieved network throughput based on the number of data packets received during the mission time. The number of packets sent are more than the number of packets received since the source continuously transmits at a consistent rate of 54 Mbps while there may not be an available route to the destination. Packets not received due to broken or inaccessible link are dropped. The destination node is able to receive packets if the source is within its communication range or if there is a route available through relay nodes and has access to the communication channel. Figure 3 shows the achieved network throughput as the number of transmitting source nodes are increased from $1-9$. We chose MAV0 (see Fig. 2) as the source node when 1 node is transmitting, MAV0, MAV1 and MAV2 when 3 nodes transmit and so on. Free space channel propagation model is used for this simulation. We observe that RS outperforms LAR and achieves approx. 10% higher network throughput since it utilizes the trajectory information to calculate the route from source to destination. This means that whenever a source gets a disconnection a new route (if available) is already calculated relinquishing the route error and route discovery overhead.

Figure 4 shows the corresponding packet inter-arrival time at the destination node i.e. the time interval between the received packets. We see less packet inter-arrival time for RS since as soon as the source desires to transmit, it already has the route (if available) to the destination and the transmission starts without a route discovery after initially acquiring knowledge of the neighbor nodes.

Figure 5 shows the achieved network throughput with increasing source nodes using Rayleigh channel propagation. Rayleigh fading model is reasonable when there is no line of sight between the sender and receiver and the incoming radio waves are received after being reflected or scattered by objects in the environment. We can observe that the overall achieved network throughput with Rayleigh fading is less compared to the free space model, which is expected but RS still outperforms LAR and achieves approx. $2\%-5\%$ higher network throughput.

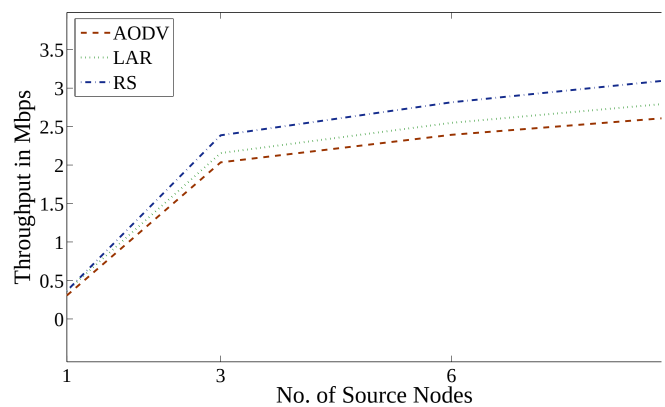

Figure 3: Achieved network throughput using free space channel propagation model

Until now, we have observed that the overall achieved network throughput for RS $>$ LAR $>$ AODV. We are now interested to evaluate individual performance of the MAVs in terms of the number of packets received and compare them using AODV, LAR and RS protocols. Figure 6 and Fig. 7 shows the cumulative sum of the received packets for MAV1 and MAV2 respectively, when three source nodes MAV0, MAV1 and MAV2 transmit simultaneously to the destination node. We chose MAV1 and MAV2 to evaluate the perfor-

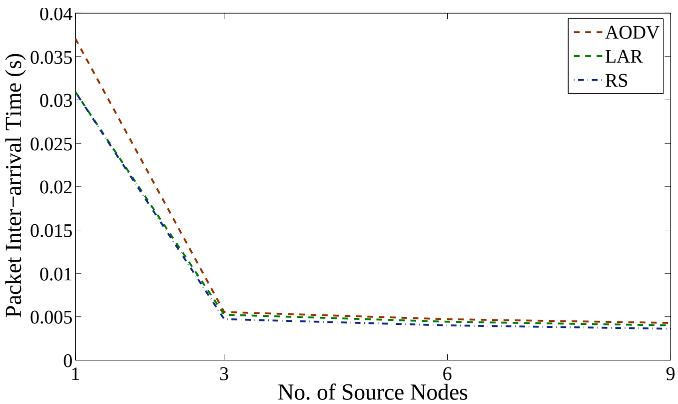

Figure 4: Packet inter-arrival time

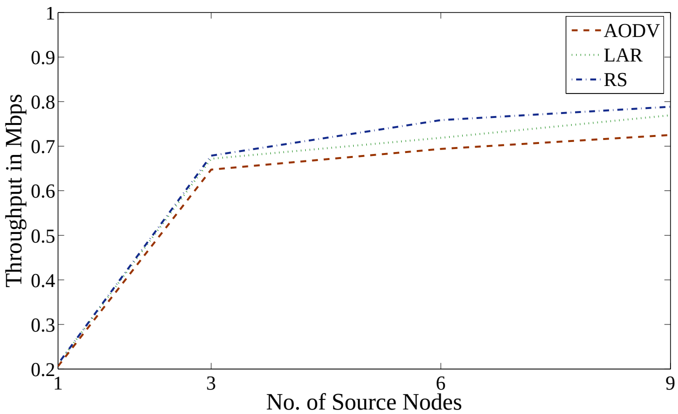

Figure 5: Achieved network throughput using Rayleigh channel propagation model

mance of a node (MAV1) that is relatively closer and requires less number of hops to connect to the destination and a node (MAV2) that it is relatively further and requires more number of hops for connectivity during the mission.

We observe that the individual comparison shows diversity at different time instances i.e., although RS performs better in terms of the sum of received packets and achieved throughput but at some time instances AODV or LAR performs better, e.g. the cumulative sum of received packets in Fig. 6 for MAV1 was better with AODV until 700 s and for MAV2 in Fig. 7 LAR performed better until 200 s. Although it depends on when a node gains access to the channel at a particular time instant but the results show that maintaining the route knowledge is helpful for achieveing higher performance in terms of the total number of packets received. However, RS still lacks achieving better performance individually during the complete mission time. This means that there might be better possible links to the destination at some time instances that are not being utilized by the RS protocol. We so believe that better link throughputs can be achieved with a link aware routing algorithm. We intend to investigate this as our future work.

Also, since our mission is to provide coverage to multiple events through multimedia traffic, we need to evaluate if the achieved throughput is sufficient to support such a scenario. From Fig. 3 the average network throughput is around 0.7 Mbps when three MAVs in the network transmit. In general the lowest quality MPEG video traffic requires 192 Kbps of data rate. Considering the throughput results achieved, it can be stated that with this setup multimedia traffic can be supported but the quality can be adapted at the application layer based on the available data rates at particular time instances. However, a good quality video link is required to be maintained during the mission time. Further improvement can be added with a link aware protocol and adding Quality of Service support at lower layers.

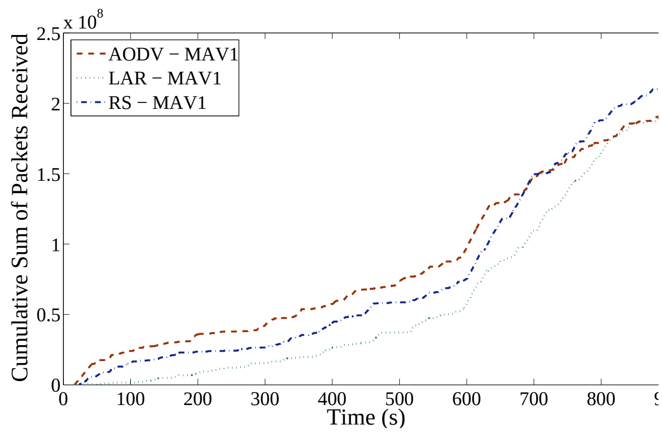

Figure 6: Cumulative sum of packets received from MAV1 while MAV0, MAV1 and MAV2 simultaneously transmit to the destination node

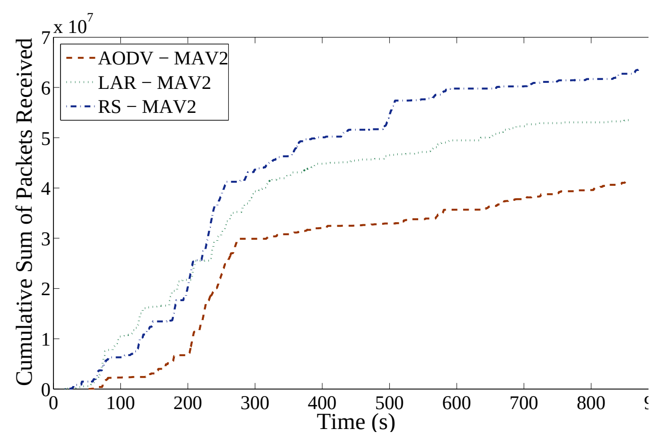

Figure 7: Cumulative sum of packets received from MAV2 while MAV0, MAV1 and MAV2 simultaneously transmit to the destination node

4.2 Coverage Mission

We now investigate the performance of our proposed protocol for the coverage mission scenario. The trajectories for this scenario that MAVs follow are computed while demonstrating a multi-MAV system that provides a high quality overview image of a given area of interest as shown in Fig. 8. The paths are then optimized based on the computed picture points [13] to provide maximum aerial coverage in the given mission time. The maximum mission time is set to 17 minutes considering the energy constraints of the quadrotors. The idea here to simulate using the real data set mission paths is that these paths resembles to our defined mission scenario of providing coverage through multimedia transmission to multiple areas of interest. The computed trajectories for the coverage mission scenario are shown in Fig. 9. Again, the destination node denoted by ★ is kept stationary and all other nodes transmit while they are moving. All other parameters are kept the same as given in Table 1 except for the simulation time which is set to 1000 s since some MAVs completes their path in this time.

Figure 8: Overview image of the area of interest for coverage mission

All MAVs start and stop at the same point and so in general they are initially and at the end closest to the destination node. Therefore, higher throughput is achieved at the start and at the end of the mission or whenever the node gets closer to the destination. It is also important to note that some paths are shorter than the others and so remain within the communication range of the destination. A MAV might thus only need two hops to transmit its packets to the destination and communicates directly otherwise.

Figure 10 shows the cumulative achieved network throughput using Free space propagation model for the coverage mission scenario. MAV0 (see Fig. 9) is the source node when 1 node is transmitting, MAV0, MAV1 and MAV2 when 3 nodes transmit and so on. The proposed Route Switching algorithm still performs better than LAR although not much of a gain is visible. The reason here is that only two hops at max. are required for source to destination, otherwise the source connects directly to the destination. However, since the route is already calculated and known a slight improvement in the achieved throughput is noticed.

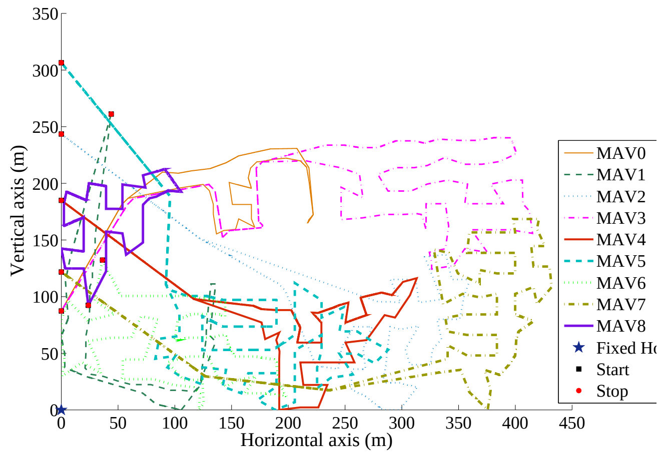

Figure 9: Trajectories: MAVs follow mission paths

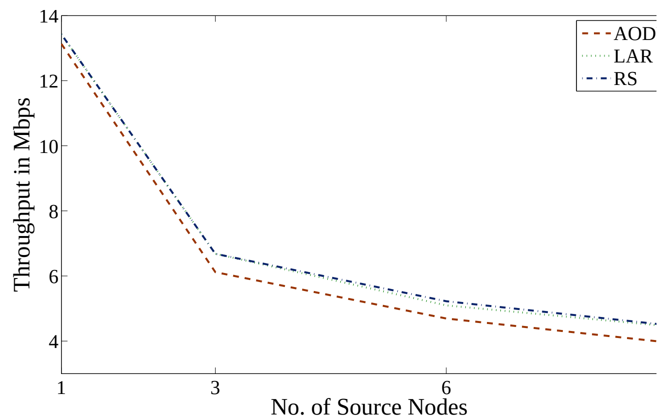

Figure 10: Achieved network throughput using free space channel propagation model for the mission scenario

5 Conclusion & Future Work

This paper analyses network performance in terms of achieved throughput and packet inter-arrival time of existing routing protocols for multi-MAV system to provide coverage to multiple areas of interest. We propose a route switching algorithm that exploits path information for calculating route from source to destination to overcome route discovery and route error overhead. However, this comes with the storage cost of maintaining the path information of all the nodes in the network and computational cost for calculating routes from each source to the destination. We used 802.11a radio interface where each MAV continuously transmits traffic at 54 Mbps to the ground station. Simulation results show that the proposed route switching scheme outperforms LAR and AODV protocols by achieving higher network performance in terms of throughput where the trajectory information is known a priori. The performance can further be improved by adding QoS support to gain fairness among the nodes, link awareness at the network layer for better connectivity and adaptability at the application layer based on achievable data rates. Our future work will focus on evaluating the overhead cost of the proposed RS algorithm and developing methodology for a link aware routing in a multi-MAV networked environment.

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