MULTIHOP ROUTING OF TELEMETRY DATA IN DRONE SWARMS

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ABSTRACT

In 2015, a group of Naval Postgraduate School (NPS) professors and students set the record for largest fixed-wing unmanned aerial vehicle (UAV) swarm flown at one time. The swarm had 50 vehicles flying simultaneously and successfully demonstrated distributed decision-making with all processing occurring on swarm vehicles rather than a centralized control station. Much of the decision-making is based on telemetry data that is continuously streamed from all the nodes. At that time all telemetry data was broadcast in a single-hop radio environment using 802.11n in infrastructure mode. In the future, drone swarm distribution and mobility patterns will necessitate multi-hop communications for this telemetry data. This paper models the network currently used by the NPS drone swarm as well as potential future topologies and evaluates candidate multihop routing protocols for this application.

INTRODUCTION

In the natural world around us, swarms have demonstrated a high degree of success. Bees, ants, termites, and naked mole rats maintain large groups that distribute tasks among individuals in order to achieve great things for the success of the colony. Fish, birds, and bats move and swirl in great numbers without colliding. Man has sought to reproduce these working models.

One key aspect that the natural models share is a form of reliable communication between individuals. Information at the small scale builds to achieve goals at the large scale. For a swarm of aerial vehicles, that communication is likely over some form of 802.11 network. This work models the network currently used by a swarm of fixed-wing aerial vehicles developed at the Naval Postgraduate School (NPS) and compares its performance to Delay (or Disruption) Tolerant Networks (DTNs) in order to observe tradeoffs between potential routing protocols for the current swarm configuration as well as future larger scale swarms.

In 2015, a group of NPS professors and students set the record for largest fixed-wing unmanned aerial vehicle (UAV) swarm flown at one time [1]. The swarm had 50 vehicles flying simultaneously and successfully demonstrated distributed decision-making with all processing occurring on swarm vehicles rather than a centralized control station. This swarm uses broadcast messaging, and no multi-hop routing is implemented.

This makes for a low latency networking scheme when all entities are within broadcast range. Where the swarm runs into problems is scaling and future sub-swarm missions. Fifty vehicles is the current highest concentration of vehicle achieved using broadcast over UDP with application layer messaging. It is not currently known how many vehicles will bring the network to saturation nor how far the vehicles may travel before losing the ability to communicate with the ground station. Vehicles have been flown as far as 2 kilometers (km) away and 850 m of elevation away from the ground station (at the limits of the testing grounds) without losing connectivity. As mission behaviors become more advanced, it may be necessary to test these limits. At this point, a routing protocol that does not overly stress the bandwidth but allows intermediary vehicles to relay messages through the swarm would prove beneficial.

This research constructs a model of the ad hoc communication network used by a large number of fixed-wing UAVs flown by NPS faculty and students in order to determine the best parameters by which to measure successful packet delivery, and compare its performance to other network protocols that might provide better performance.

BACKGROUND AND RELATED WORK

This section introduces the necessary concepts of UAV swarm research; how it has progressed, common issues, and research towards finding solutions to these issues. Very often, dynamic networks have properties unique to their environment and/or purpose. Solutions for one group may not work for another without changes to the routing protocol. As a result, there are many variations to the basic founding ideas to consider.

A. Swarm Networking Issues

Aerial swarms have the capacity to move quickly, not only in relation to the ground and base station, but also in relation to other vehicles. The swarm is composed of the NPS-designed and built Zephyr II UAV, which is a 2.5 kilogram (kg) fixed-wing vehicle based on a commercially available platform from Ritewing. It has a wingspan of 1.45 meters (m) and a cruising speed of 18 meters per second (m/s) [1]. The NPS swarm uses no routing protocol. Rather, it broadcasts all messages over the 802.11n wireless network and relies on the vehicles to determine from the application-level message header whether to drop a message not intended for that vehicle, or accept the message and respond accordingly.

R. Stefano *et al*. [2] implemented a fixed wing swarm with a cruising speed of about 16 m/s. This high mobility creates a highly dynamic topology wherein links are frequently formed and broken. Stefano *et al*. addressed this issue with a routing protocol that uses knowledge of Global Positioning System (GPS) data to predict the best routing path over the 802.11n wireless network.

Another issue that arises for mobile aerial vehicles is the ability for them to travel away from the base station and/or other vehicles. This allows for a larger operating area as vehicles disperse throughout an unbounded three-dimensional space, which may benefit the mission. The result is highly heterogeneous node dispersion and clustering. Power must be split between communications, flight, and sensors. In any case, until aerial swarms are able to scale well, they will have lower node density than sensor networks to which they are sometimes compared [3].

At the transport layer, Rohrer *et al.* [4] examine the shortfalls of using a TCP/UDP/IP in an aeronautical environment. The TCP routing protocol was designed for long-lasting connections along an established path. Attributes of TCP, like the three-way handshake, slow start algorithm, and congestion control algorithm, do not allow this routing protocol the flexibility to deliver packets quickly in an aeronautical node environment. UDP is not encumbered by the same restraints as TCP, but offers no acknowledgment that packets were delivered to the destination [5].

Bandwidth is yet another constraint in aerial vehicle swarms. When all the nodes are trying to send messages, and the number of nodes is significant, bandwidth can be overwhelmed. Message conveyance is not the only stress on bandwidth, though. Overhead from routing protocols can be the most significant taxation on bandwidth. Section C. provides more detail about the kinds of overhead produced by multi-hop routing protocols.

B. Current Swarm Networking Tactics and Models

The NPS swarm uses an in-house application for vehicle-to-vehicle and vehicle-to-ground messaging. User Datagram Protocol (UDP) broadcast is used to transmit these messages over an 802.11n ad-hoc wireless network. The application-layer is responsible for accepting messages and sending replies when appropriate. Several distinct message types are utilized, a number of which are transmitted at regular intervals. For safety reasons, a heartbeat message is sent from the ground station to the vehicles at an interval of 1 hertz (Hz). If a vehicle does not receive that message for a period of 30 seconds, it aborts its current mission and loiters at a pre-designated point to attempt to re-establish its link with the ground station. If the vehicle does not receive an update within two minutes, it executes its autonomous landing procedure [1].

Individual vehicles send flight status messages to the ground station at a rate of 2 Hz. Vehicles also send pose messages to update the ground station and other swarm vehicles as to their current state at a rate of 10 Hz [1]. The last synchronous message is the red pose message, transmitted by a special purpose ground station, the arbiter, as a means of providing 'virtual sensor' information during competitive multi-swarm events [6].

In addition to these synchronous messages, a number of asynchronous messages are provided. These messages address a number of special purpose requirements such as assignment of vehicles to sub-swarms for tasking, initiation and termination of swarm behaviors, direction or parametrization of individual vehicle actions, and the exchange of behavior-specific information between vehicles [1]. Asynchronous messages can be broadcast to the entire swarm or directed to a specific vehicle or ground station (although still transmitted as a UDP broadcast message).

Real-world vehicle-to-vehicle packet delivery rates for the 50-UAV swarm event were described in [1]. Given their frequency and contents, synchronous messages comprise the bulk of the NPS swarm communications requirement. This work will therefore focus on analysis of synchronous message traffic within the NPS swarm.

Examples of other swarms and their techniques include:

- 2004: Three quadcopter UAVs using GPS navigation and a Bluetooth connection with a ground station that is able to adjust positioning data, and send navigation commands as waypoints. Commands are given to each vehicle through an established end-to-end Bluetooth connection. Vehicles are not able to exchange information [7].
- 2013: Three fixed-wing UAVs in a leader-slave-slave relationship. Each vehicle is given updated information about the flight path throughout the flight from a ground station via a modem using a point-to-multipoint setting. Vehicles are not able to exchange information. Safety personnel on the ground stand by to take control with RC controllers (one person per vehicle) [8].
- 2014: Ten quadcopter UAVs in a decentralized swarm. Each vehicle is responsible for collision avoidance calculated with GPS data shared between vehicles via Xbee wireless radios.

These position reports are sent in a broadcast mode between relative neighbors without establishing an end-to-end connection. Flight status information is sent to the ground station for monitoring and record keeping. The vehicles receive no information from the ground station pertaining to flight or organization. One individual can safely run the swarm due to the high level of autonomy [9].

- 2016: Intel demonstrates a 500+ quadcopter UAV lightshow swarm. Little information is available on the communication methods used, other than that they are controlled from a single computer and the choreography is preprogramed. This allows the vehicles to execute their flight plan without communicating with other vehicles [10].

- 2017: Ehang demonstrates a 1000+ quadcopter UAV lightshow swarm. Little information is available on the communication methods used.

- Ongoing Research: The swarming micro air vehicle network (SMAVNET) uses up to ten small fixed-wing UAVs (420g, 80cm wingspan) to conduct swarming behavior and communication experiments. Collision avoidance is accomplished via vehicle-to-vehicle communications while in flight. Neither operator-provided information nor on-board sensors are used to detect the in-air location of other vehicles. The SMAVNET team uses commercially available wifi hardware on their vehicles. Swarming behaviors are either reverse-engineered controllers or modeled after biological examples such as ants leaving pheromone trails [11].

One potential solution to many issues described is the use of a Mobile ad hoc network (MANET). MANETs are groups of mobile nodes with the capability to receive, route, and transmit network traffic. These nodes are free to move which creates a dynamic topology. Mobility comes at the cost of being dependent upon a limited energy source as well as relying on wireless connections resulting in bandwidth constraints. These routing protocols fall in three different categories; proactive (table based), reactive, and hybrid schemes [12]. Originally designed to bridge the vast distances in space, DTN routing protocols use a store-and-forward tactic to deliver bundles of data when an end-to-end connection between source and destination is not possible [13]. There are many kinds of DTNs. Their design and performance are dependent upon their environment. As the NPS swarm grows in scale, multi-hop routing protocol will likely be necessary.

The NPS swarm's various messages have different reliability and latency requirements. Some, like the heartbeat message, may not require every message to reach a vehicle, as long as one does within a defined window. It is not vital that missed heartbeats be delivered once the next has been sent by the ground station. Others, like asynchronous messages carrying behavior commands, must reach their destination or be able to inform the ground station that it was unable to reach the destination or vehicles will not join the correct behavior. More than one protocol may be chosen to work within the swarm's communication network, each chosen for a message that uses that protocols strengths to the swarms advantage. Section C. reviews protocols that represent various tactics used in network routing. Some are well established, like the four applied in this study (DSDV, OLSR, AODV, and Epidemic). Others are relatively new as more variation is needed for unique wireless networks such as flying ad hoc networks (FANETs), or disruption-tolerant networks (DTNs) [14].

METHODOLOGY

This section provides a review of the simulation built to model the NPS swarm in ns-3. Ns-3 is a discrete-event network simulator designed by the members of the NS-3 Consortium [15]. It contains many helpful tools within its library that replicate the behavior of real-world networks.

Table 1: Message Parameters

Message	Data Rate	Packet Size	Frequency
Heartbeat	160 bps	20 Bytes	1 Hz
Flight Status	768 bps	48 Bytes	2 Hz
Pose	4480 bps	56 Bytes	10 Hz
Red Pose	3200 bps	40 Bytes	10 Hz
Asynchronous	as required	variable	as required

Individual NPS swarm messages each have unique characteristics affecting behavior at the link layer that must be captured in the model. Synchronous messages described in Section B. are broadcast at message-specific frequencies and have standard sizes. Within the simulation, each message type is also assigned a unique port over which to be received. All messages, regardless of type, include a standard 16 Byte header added at the application layer. Applications were started at staggered times in order to ensure that collisions were not generated by artificial synchronization.

Table 2: Swarm Configurations

Mobility Model	Ground Station	Sub-swarms	Sub-swarm nodes	Simulation nodes
6 v 6	1	2	6	12
10 v 10	1	2	10	20
15 v 15	1	2	15	30
25 v 25	1	2	25	50

Instead of using one of the synthetic mobility models in ns-3, the swarm nodes follow traces from real swarm flights. The NPS group can fly the swarm in a red versus blue scenario in which two competing groups attempt to target and engage all vehicles in the opposing swarm [6]. The vehicles are assigned a swarm ID, which places them in either sub-swarm one (red) or sub-swarm two (blue). After launch, each vehicle flies to its assigned altitude and begins circling a designated area. Once all vehicles are launched, there will be two columns of circling UAVs standing by for their next order, which will arrive via an asynchronous message. The two sub-swarms will come together and simulate an air-to-air engagement, then separate back into their designated columns. After all behavior scenarios are complete, individual UAVs will be told to land until all vehicles are safely on the ground. Table 2 illustrates the composition of the four swarm events used for the mobility model in this work.

C. Routing Protocols

Once the simulator reproduced message traffic in a broadcast configuration, code was added for additional routing protocols that are representative of the major categories traditionally used in ad hoc networking. The ns-3 library provides a number of useful ad hoc routing protocols:

- OLSR: a link-state proactive protocol is able to maintain tables for immediate addressing of the shortest path [16].

- DSDV: a distance-vector proactive protocol [17].

- AODV: a distance-vector reactive protocol [18].

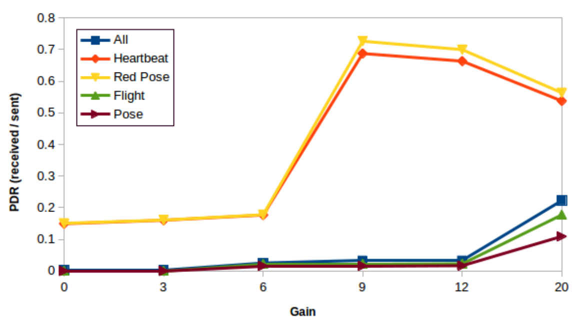
- Epidemic: a simple flooding-based DTN routing protocol [19].

Though these protocols are not optimized for use in FANETs, they can be treated a representatives of fundamental routing tactics and are therefore useful in demonstrating strengths and weakness inherent to all protocols that fall within these respective categories. We vary the simulated radio antenna gains to emulate varying node densities and radio coverage ratios. Transmit and receive gains were always set to matching levels. Simulation experiments were conducted swarm trace data for twelve, twenty, thirty, and fifty vehicle events.

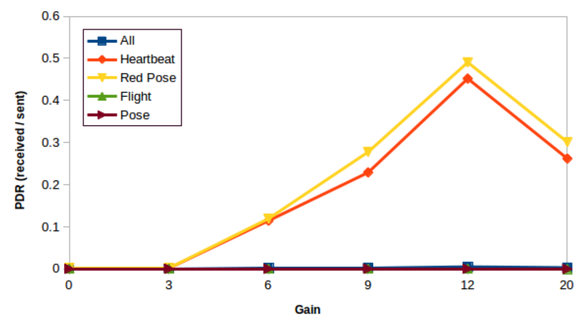
The following metrics are utilized for quantitative comparison of protocol performance:

- Packet Delivery Ratio (PDR): calculated by dividing the number of messages received by the number sent.

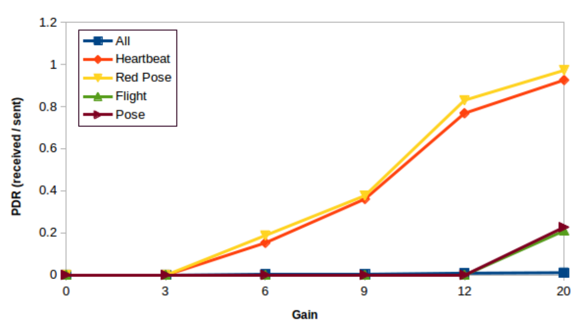
- Overhead: message copies, retransmissions, and routing control messages.



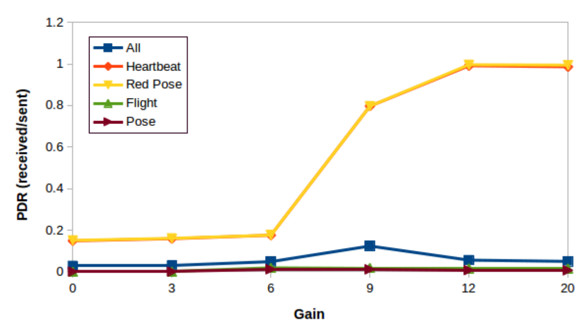
(a) Broadcast 6 v 6 Swarm



(b) Broadcast 10 v 10 Swarm



(c) Broadcast 15 v 15 Swarm

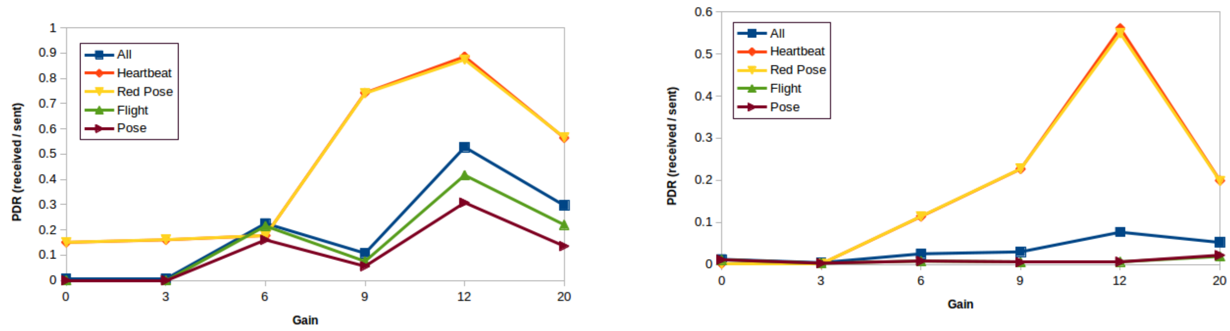


(d) Epidemic 6 v 6 Swarm

Figure 1: Packet Delivery Ratio

RESULTS AND ANALYSIS

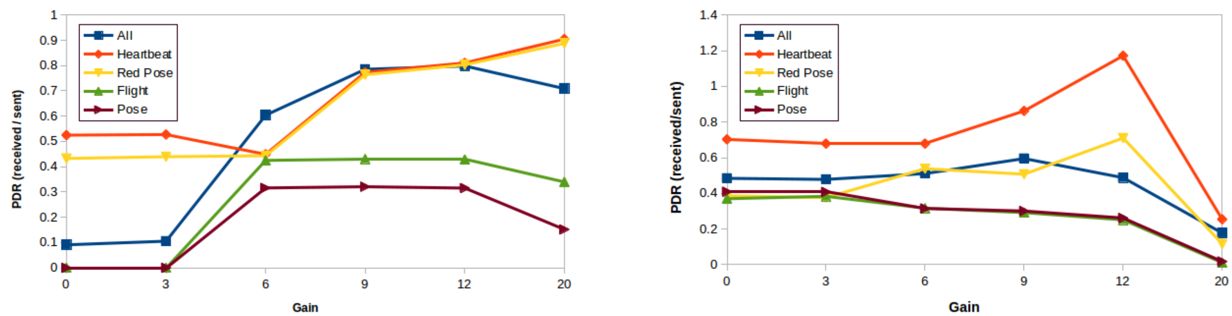
This section reviews the results from the 120 simulations and highlight a number of illustrated trends and relationships.



(a) 6 v 6 Swarm

(b) 10 v 10 Swarm

Figure 2: Packet Delivery Ratio Using DSDV



(a) 6 v 6 Swarm

(b) 25 v 25 Swarm

Figure 3: Packet Delivery Ratio Using AODV

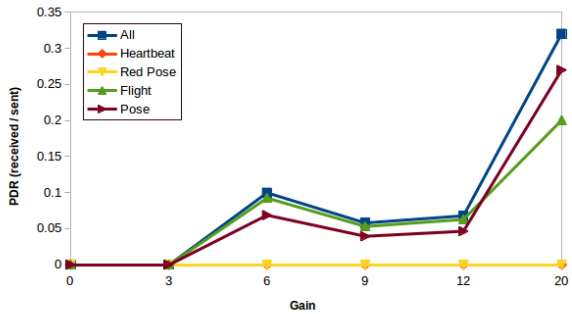
Packet delivery rations (PDRs) for flight and pose messages are calculated by dividing total messages received by total messages sent.

In general, the broadcast method improves as the gain in the environment increases, as shown in Figures 1a, 1b, and 1c. Packets traveling from the vehicles to the ground achieved a higher packet delivery ratio than those traveling from the ground station to the vehicles. Heartbeat and red pose messages destined for the vehicles are close in values and patterns. Likewise, flight status and pose messages also behave in a close relationship.

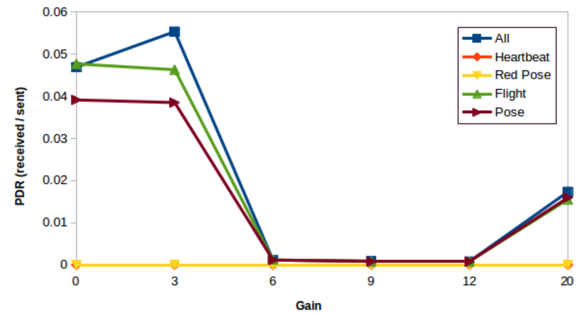
DSDV's best performance was in the gain of 12 environment across all swarm sizes (2a and 2b).

AODV's PDR performance (Figures 3a – 3b) is best in the smaller swarm of 6 v 6 after reaching the gain of 6 environment. Delivery rates are low in the 10 v 10 and 15 v 15 swarms. The 25 v 25 swarm maintains around 50% of packets delivered, peaks in the gain of 12 environment and then crashes in the most inclusive gain environment. This crash is in contrast to the behavior in the 6 v 6 swarm, which performs closer to expectations.

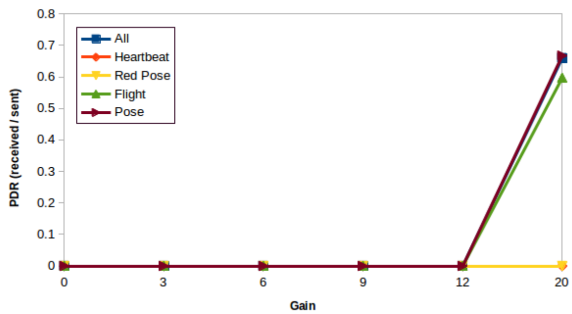
OLSR's packet delivery rates (Figures 4a – 4d) are quite poor. Rarely are more than half of sent packets received. The vehicle-destined heartbeat and red pose messages, which have thus far outperformed all other messages using the other routing protocols, lay at the bottom of these graphs. It observed in the trace files that OLSR has a difficult time creating the routing tables for vehicle destinations in such a dynamic topology. Looking at the raw trace files generated by the simulator, one can see numerous routing table messages. They far outnumber actual message traffic. Their frequency creates many collisions at the data link layer.



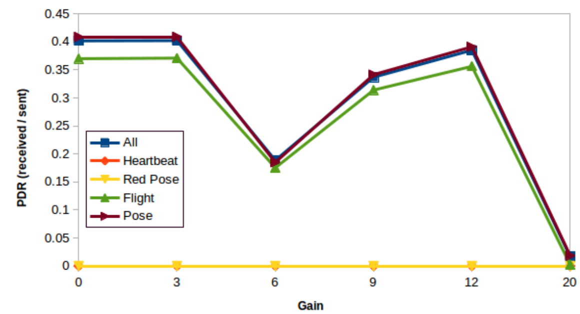
(a) 6 v 6 Swarm



(b) 10 v 10 Swarm



(c) 15 v 15 Swarm



(d) 25 v 25 Swarm

Figure 4: Packet Delivery Ratio Using OLSR

Epidemic's PDR performance in the 6 v 6 swarm shows that it can deliver messages to the nodes as the environment becomes more inclusive (more nodes able to be touched by the flooding) but the nodes are never really able to deliver messages to the ground (Figure 1d).

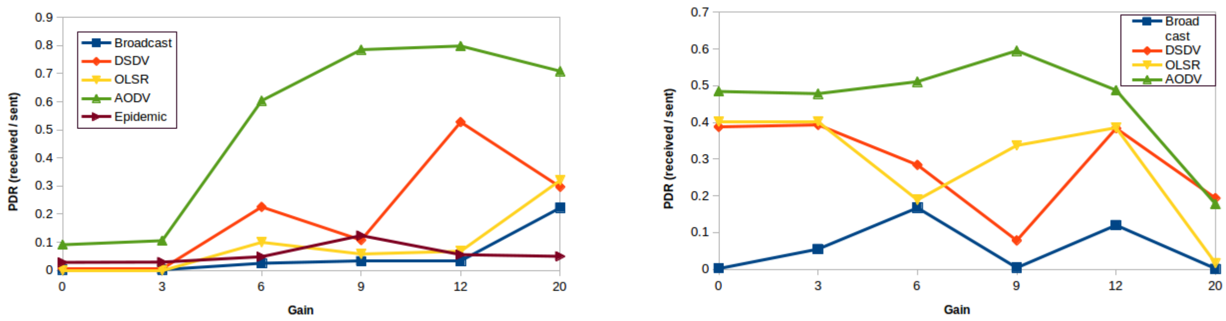
Figures 5a and 5b give a final perspective of PDR by placing the routing protocols' all messages side by side per swarm size. AODV PDR remains above them all in every swarm. The recovery of stats in the 25 v 25 swarm is even more evident.

CONCLUSIONS AND FUTURE WORK

Some of the results were unexpected. No protocol consistently performed close to expected values. Those protocols that generated significant overhead created collisions or failed converge the network Not only did overhead create conditions for numerous retransmissions, but they had low message delivery metrics. The protocols with less overhead fared better.

AODV, as a reactive protocol, was able to discover multi-hop routes in restricted connectivity environments but was able to back off when nodes operated in a highly connective environment. It was able to perform across more environments than any other protocol both when delivering messages to the ground station and to nodes. Even in the 15 v 15 Swarm, where many protocols failed to deliver messages to the ground, it was able to deliver some messages.

DSDV had similar performance numbers to broadcast which implies it did not harm message delivery while updating its neighborhood routing tables but it also did not improve delivery in environments when single-hop routing was not available. OLSR, the other proactive routing protocol, was unable to deliver messages to the vehicles in all swarm sizes. The highly dynamic node topology caused OLSR to flood the network with routing table update messages.



(a) 6 v 6 Swarm

(b) 25 v 25 Swarm

Figure 5: Packet Delivery Ratio for all protocols

At this time, the 1-hop communications used by the NPS swarm is working consistently with 50 airborne nodes. As NPS swarm experimentation scales up, we recommend choosing a routing protocol that is either reactive in nature or is focused primarily on reducing overhead to avoid exhausting the limited bandwidth available. Future routing protocols may need different limits, rules, or settings, based on whether the message is traveling ground to node or node to ground.

In future it would be useful to perform the same simulation with additional mobility traces of the same numbers of nodes, in order to understand the generality of the results. Averaging PDRs at the same size but with different flight patterns could help factor out extreme cases based purely on lucky or unfortunate flight paths of certain vehicles. The data sets might also be more clear if take-off and landing flight data were excluded from the mobility models.

At this time, the ns-3 libraries are limited to traditional routing protocols for MANETs. Networking researchers have had more opportunity and motivation to work with them than to network UAVs. It would be extremely beneficial to develop and add to the libraries various protocols that are more feasible or specifically designed for FANETs and DTNs.

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