EFFECTS OF SWARM DENSITY ON MULTIHOP DRONE TELEMETRY DATA

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ABSTRACT

Bandwidth being a limited resource in airborne telemetry networks, drone swarms are particularly challenging to instrument due to the number of airborne nodes involved. Even a modest amount of data being transmitted by each node may overwhelm the network. Prior work has evaluated these effects in a number of drone swarm mobility scenarios, and shown the difficulty of achieving reliable data delivery. However, those results do not distinguish between data loss due to congestion of the available spectrum, and loss due to changing network topologies or disconnection due to mobility. In this work we attempt to isolate those effects by keeping a simulated drone swarm stationary, and focussing on the telemetry data delivery due to changing the size and density of the swarm. We compare the performance using no multi-hop routing protocol, as well as using DSDV, AODV, DSR, and OLSR.

INTRODUCTION

Drone swarms have made numerous headlines over the last several year, attaining new thresholds of size and coordination, however it is important to node that they do so with *minimal* live communications. Individual nodes are heavily pre-programmed with their expected behaviors. Another common approach is for a single ground station to broadcast commands to the swarm (one-to-many), with no return transmissions from the drones. This is the opposite of the telemetry environment where it is important to collect data from each member of the drone swarm (many-to-one). In engineering such a telemetry network there are two possible extremes: All nodes can transmit with sufficient power to reach the/a ground station at all times, or each node can transmit with just enough power to reach their nearest neighbor, which in turn can forward their traffic to other nodes, and eventually to the/a ground station. Both solutions have pros and cons, and there is a continuum of operating points in-between.

The first approach provides low-latency communications when all nodes are within range of each other, however it introduces two problems. The first is that as the number of nodes increases, it will eventually saturate the communication channel, since no spacial-reuse is possible with this scheme. Early signs are that this will occur with swarm sizes not much larger than the current 50 nodes [1, 2]. Secondly, future mission tasking is likely to require distributing nodes geographically such that not all are in communication range of each other, as well as sub-swarm missions where the swarm splits temporarily and later regroups [3].

BACKGROUND AND RELATED WORK

In this section we examine the existing state-of-the-art in drone-swarm research.

A. Swarm Networking Issues

Drones and drone swarms may move rapidly with respect to their radio range, causing them to frequently lose and regain connectivity to ground stations and other vehicles.

In addition to network and routing layer limitations, prior work has shown TCP to perform poorly in lossy wireless environments [4], and this effect is exacerbated with each additional wireless link in the path. The TCP transport 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 algorithms were not designed for scenarios where packets are lost due to causes other than congestion, or where paths are frequently broken. UDP is not encumbered by the same restraints as TCP, but offers no acknowledgment that packets were delivered to the destination [5].

Channel bandwidth is also an ever-present constraint in telemetry systems, and can easily be overwhelmed with 10s or 100s of nodes attempting to communicate simultaneously. On one hand, multi-hop routing may help with this, by permitting more spacial reuse in the channel allocation plan, however overhead from routing protocol control messages can also consume significant amounts of bandwidth, as we show in [3].

In this work, the drone swarm is stationary, and the individual nodes are arranged in a rectangular formation having one, two, or three dimensions (a line, square, or cube respectively). The set of drone formations simulated is shown in Table 2.

Section B. reviews protocols that represent various tactics used in network routing. Some are well established, like the four applied in this study (DSDV, AODV, OLSR, and DSR). 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) [6].

METHODOLOGY

This section provides a review of the initial simulation built to model the NPS swarm in ns-3, as well as modifications made by this study to improve the mobility model and test additional routing protocols. Ns-3 is a discrete-event network simulator intended to implement the entire network stack as a platform for testing a variety of real-world networking scenarios [7]. The ns-3 Consortium developed it with the intent to improve research and education tools, and recent work shows that when compared with the ONE simulator, ns-3 provides a more robust, real-world implementation of various networking aspects [8]. The results in this paper were obtained using ns-3.29, and each parameter set is averaged over five runs with different seeds for ns-3's random number generator.

Table 1: Traffic Parameters

Type	**Data Rate**	**Packet Size**	**Frequency**
Telemetry	768 bps	48 Bytes	2 Hz

Table 2: Swarm Configurations

Dimensions	Ground Stations	Nodes
$1 \times 1 \times 1$	1	1
$1 \times 2 \times 1$	1	2
$1 \times 3 \times 1$	1	3
$1 \times 4 \times 1$	1	4
$1 \times 5 \times 1$	1	5
$1 \times 6 \times 1$	1	6
$1 \times 1 \times 1$	1	1
$2 \times 2 \times 1$	1	4
$3 \times 3 \times 1$	1	9
$4 \times 4 \times 1$	1	16
$5 \times 5 \times 1$	1	25
$6 \times 6 \times 1$	1	36
$1 \times 1 \times 1$	1	1
$2 \times 2 \times 2$	1	8
$3 \times 3 \times 3$	1	27
$4 \times 4 \times 4$	1	64
$5 \times 5 \times 5$	1	125
$6 \times 6 \times 6$	1	216

B. 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 [9]. For cases when fewer nodes are within range of the ground station, OLSR (Optimized Link-State Routing) should be able to quickly find a multi-hop pathway for the message. On the other hand, when the ground station is able to reach most or all nodes directly, link state messages will likely create overhead for unnecessary multi-hop path tables. In this case, the benefit of table maintenance will be lost and limited bandwidth resources will be used with no returned value. Also, as the number of nodes increases, OLSR will have a more difficult time converging and the highly dynamic topology will cause the generation of a large number of link state messages.

- DSDV: a distance-vector proactive protocol [10]. DSDV (Destination Sequenced Distance Vector) focuses on proactively updating distance-vector tables across the network, much like its wired equivalent, RIP. This, in turn, should result in fewer distance vector messages. The proactive nature of this protocol will still generate extra messages for table updates in a network even if all nodes are in single hop range of the ground station, thus stressing bandwidth unnecessarily.

- AODV: a distance-vector reactive protocol [11]. AODV (Ad-Hoc On-Demand Distance Vector) may have lower overhead costs when compared to proactive protocols if traffic is destined to a small subset of the nodes. These overhead cost savings should be most evident when more nodes are within single hop range of the ground station, and route discovery will not be invoked as often.

- DSR: a simple reactive source-routing protocol [12]. DSR (Dynamic Source Routing) is similar to AODV in that it forms routes on demand, only when requested, however it uses source routing instead of distributing routing tables to each hop.

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.

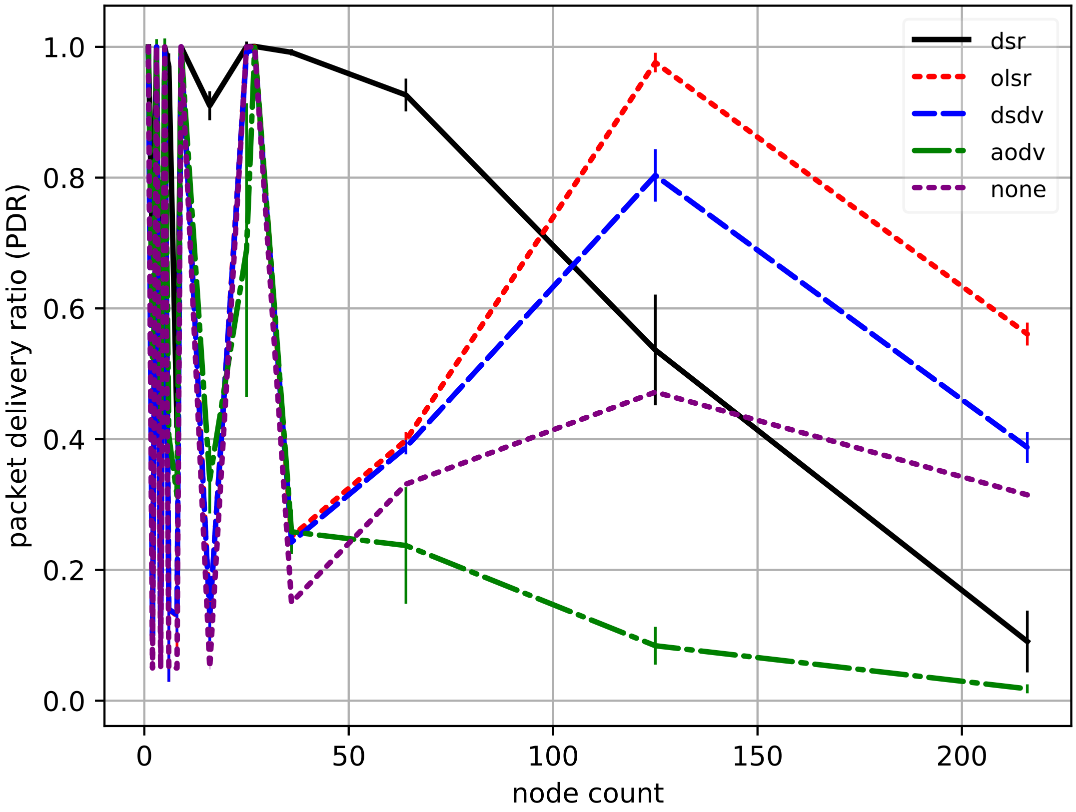

Figure 1: Packet delivery ratio vs. node count; 95% confidence intervals

C. *Traffic Generation*

In prior work we have simulated both mission and telemetry data (described in [2]), however in this case we want to isolate aspects of network performance, so we limit traffic generation to constant-bit-rate telemetry data only. Table 1 shows the relevant features of this telemetry traffic, which resulted in each node in the swarm transmitting two data-packets per second, addressed to the ground station.

D. *Experiment Parameters*

The following parameters were varied to exploit the various features of the routing protocols used:

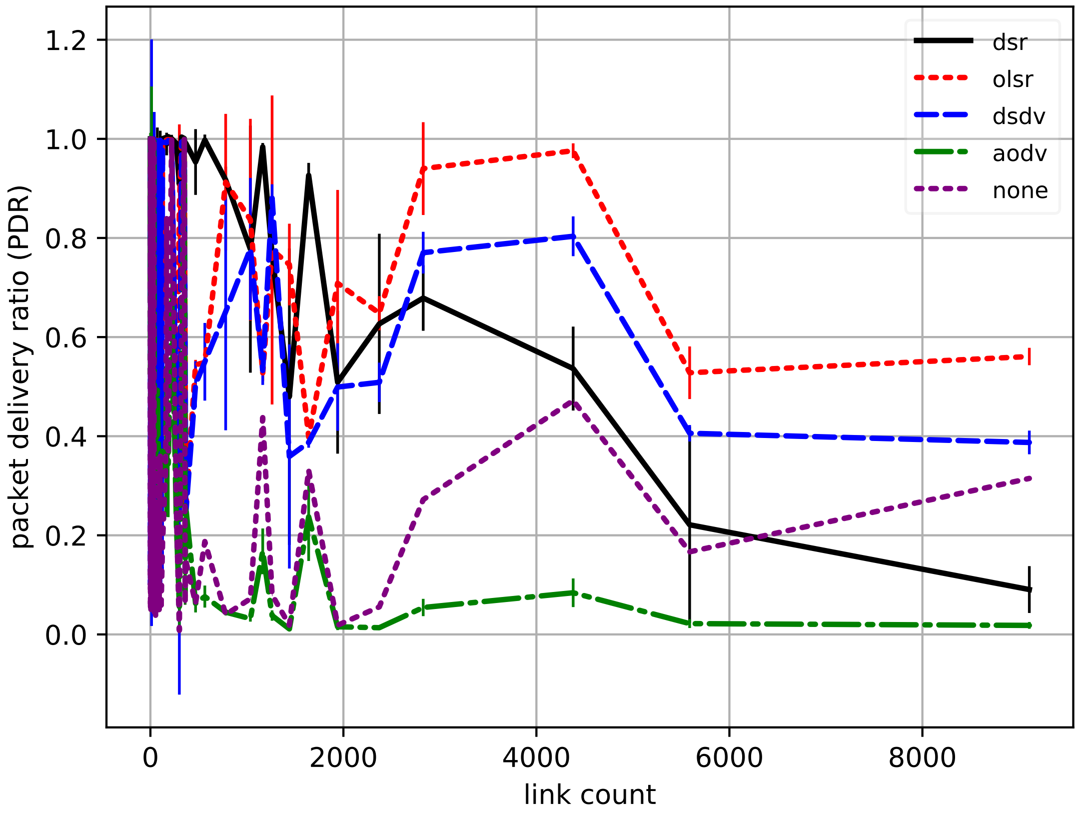

Figure 2: Packet delivery ratio vs. link count; 95% confidence intervals

- Swarm dimension: the length of each side of the swarm formation, also determining the total number of nodes in a given swarm.
- Drone spacing: the distance between drone in the (x, y, z) dimensions.
- Radio range: the transmission range (itself a function of transmit power and antenna gain) is adjusted. Together with the drone spacing, this determines the number of neighbors for each node (node degree).
- Routing protocol: the multi-hop MANET routing protocol used to deliver packets tot he ground stations, including no routing protocol.

Throughout this study, we set the node spacing parameter to 100 m. The set of radio ranges used for simulation is: 105, 145, 175, 205, 285, and 350 meters.

E. Experiment Metrics

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

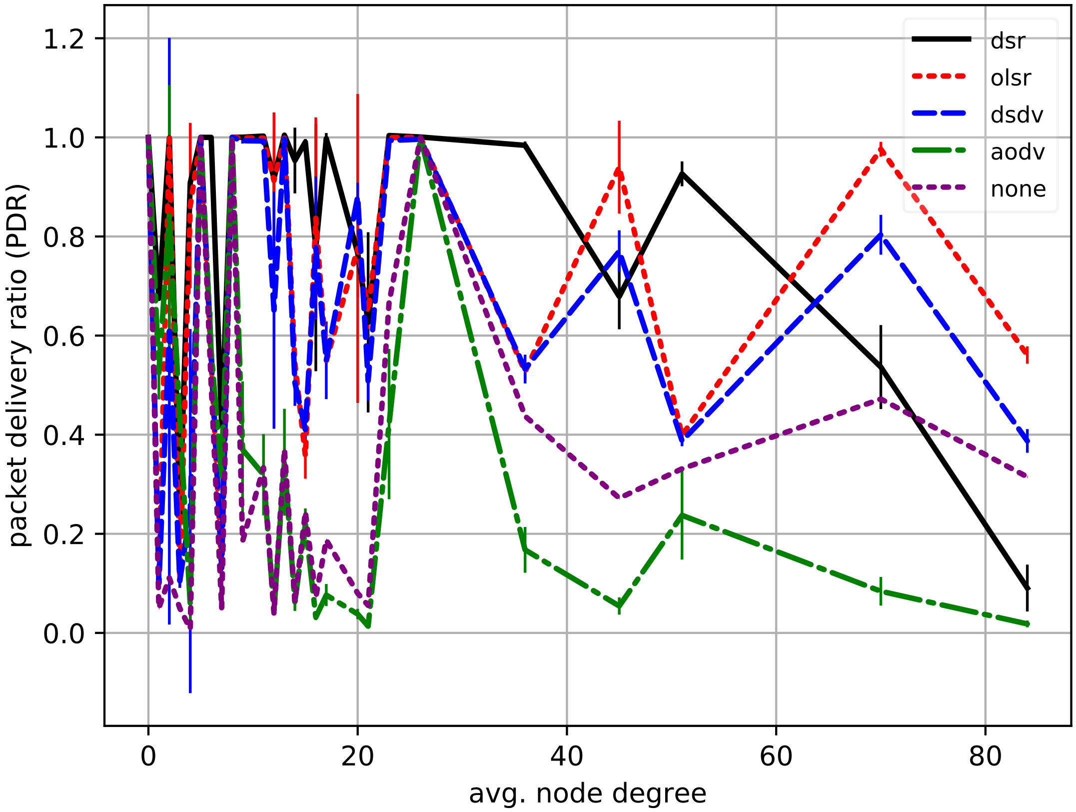

Figure 3: Packet delivery ratio vs. average node degree; 95% confidence intervals

- Packet Delivery Ratio (PDR): calculated by dividing the number of packets delivered to the assigned destination by the number sent.

RESULTS AND ANALYSIS

This section reviews the results from the 2700 simulation executions, and highlights some trends and relationships.

The initial NPS swarm simulation measured PDR (Packet Delivery Ratio) as a function of the individual messaging application, and showed that generally, broadcast is the most effective method of transmission with the swarm scenario across all applications [2]. Since the aim of this study was to elaborate on that work, and to provide a baseline for future work in studying new routing protocols in drone-warm telemetry environments, the results of this work will be discussed in a broader sense. We look at PDR as a function of node count, link count, and average node degree, to compare the performance of each routing protocol.

Significantly, and in contrast to prior work, broadcast transmission (shown as “none” in the plots) does not generally outperform the MANET protocols. Figure 1 shows unpredictable performance with small numbers of nodes, and a general decline in performance with larger numbers of nodes is increased. DSR performed the best with 64 nodes and fewer, while OLSR performed best with 125 and 216 nodes.

However, node count alone does not determine the state that must be maintained and transmitted by the routing protocols, so we next consider the link count. Figure 2 again shows unpredictable performance on the far left side, but as the number of links increase we quickly see trends emerge. DSR again does well with low counts but trends downwards, while OLSR outperforms the other protocols everywhere above 2000 links. We also note the upward trend of broadcast ("none") on the right side of the graph, and note that one of the factors in increasing link count is increasing transmission range, meaning more nodes are in range of the ground station as we move toward the right side of the plot.

Lastly we examine the relationship between average node degree and PDR. Node degree (ND) is a significant metric because it essentially captures the density of the swarm in a way that matters to network protocols. Here it is influenced both by the formation (cube ND $>$ square ND $>$ line ND) and the transmission range. Figure 3 again shows DSR performing well at low swarm densities, while OLSR outperforms it at the highest densities.

CONCLUSIONS AND FUTURE WORK

We haven't said much about DSDV and AODV so far. AODV has the lowest performance throughout the simulations, which is not surprising as a primitive reactive MANET routing protocol. It is included here for completeness, but will likely be omitted in future work. DSDV is a primitive proactive protocol, so it is surprising that it performs as close to OLSR as it does. We will continue to use it as a comparison point in our work, however expect it to struggle as mobility increases. A final observation on PDR is that these outputs show that as the node density increases, complexity also increases, as evidenced by the downward trend in protocol performance across increasing swarm densities. The increased complexity in neighbor and route discovery makes it significantly more difficult for the MANET protocols to operate at a high capacity. Of the protocols investigated in this work, OLSR is best able to manage that increased complexity.

ACKNOWLEDGMENTS

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