Routing Protocol Performance over Intermittent Links

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ABSTRACT

Communications among mobile, tactical nodes presents a major military challenge. The use of MANET (Mobile Ad Hoc Network) protocols provides a possible solution for military nodes, including those in an airborne network. However MANET research has primarily focused on ground-based studies, using vehicular speeds and in many cases random mobility patterns. Nodes of an airborne network travel at speeds significantly faster than ground vehicles, and fly in coordinated paths not modeled by random mobility. In addition, the quality of the radio links for airborne nodes varies with time, due to interference, range, or antenna occlusion when banking. These characteristics make it impossible to extrapolate existing MANET research results to the airborne network. In this paper we present a simulation evaluation of MANET protocol performance for an airborne environment, with the intent to identify a routing protocol that can best deal with the dynamics of an airborne network.

A scenario involving widebody aircraft trajectories was modeled in OPNET. Intermittent link outages due to aircraft banking were modeled by use of a notional radio link, antenna model, and modified OPNET source code that reflects positional antenna gain, including antenna occlusion when an aircraft banks. Within this scenario environment, four MANET protocols (AODV, TORA, OLSR, OSPFv3-MANET) were run on the airborne nodes with metric collection of protocol overhead, packet delivery ratio, and packet delay. Simulation results and analysis of the protocol performance for an airborne network are presented here. Additional issues and future areas of research are also identified.

1. INTRODUCTION

This paper presents an evaluation of MANET protocol performance for an Airborne Network. There have been numerous studies evaluating the performance of MANET protocols, but for the most part the mobility models of these studies consist of random waypoint mobility at ground-based vehicular speeds, no more than 20 m/sec with focus on the scalability of MANET networks, up to 1000s of nodes. Characteristics of an airborne environment are very different. Aircraft speed is significantly faster than ground vehicles; military aircraft fly in coordinated paths not modeled by random mobility and the number of nodes in an Airborne Network at one time will be much less than 1000. Airborne radio link quality is time-varying due to interference, range, jamming, or antenna occlusion during banking. This simulation study focuses on modeling these characteristics in a realistic airborne scenario in which MANET protocol performance can be evaluated. In addition to incorporating realistic speeds and flight paths of widebody military aircraft, the physical link performance includes an antenna model that accounts for antenna occlusion during aircraft banking.

Routing protocols require connectivity among nodes. For wirelined networks, this connectivity is stable with occasional disruptions, but for airborne networks, disruptions are the norm. Connectivity is interrupted due to inter-aircraft distances beyond radio range and outages from multiple causes as noted above. This study explores the performance of MANET protocols in the presence of connectivity lapses that would be experienced in a realistic scenario. One specific scenario is used to gain insight into the issues facing an airborne network as well as to characterize a baseline MANET performance as a point of comparison for future studies. This does not imply that the scenario used in this study represents the only realistic airborne network scenario. Future work will require modeling of additional realistic scenarios with a goal of development of generalized link models for airborne network studies.

It is important for simulation studies to recognize issues related to the validity of Modeling & Simulation studies for MANET protocols and these concerns are discussed in Section 2. Section 3 presents specifics of the OPNET MANET protocol models and Section 4 describes in detail the simulation scenario used in these studies. Simulation results are presented in Section 5. Finally, conclusions and areas of future research are presented in Section 6.

2. MANET Simulations

Journals and conferences have been filled with performance evaluations of MANET protocols, but no single protocol has emerged as the optimal solution for all cases. For practical reasons, many of the evaluations have been done via simulation rather than experiments and recently, questions have been raised about the credibility of simulations used to evaluate MANET protocol behavior. Reference [1] reviewed 114 published MANET simulation papers and identified issues leading to lack of reliability in MANET simulation-based studies. The shortfalls included lack of detail to support repeatability, lack of model validation and verification, and lack of recognition of initialization bias. The lack of reality in mobility models and the need for simulation validation is pointed out in [2] while [3] compares the inaccuracies of simulations to actual experiment results. This study seeks to address the issues reflected in these papers by incorporating a reality-based scenario that includes a physical layer model that has been measured against live exercises in an attempt to bridge the gap between simulations and reality.

Legacy MANET simulations have focused on general-purpose evaluation of protocol performance across a continuum of scenarios, based on the premise cited in [1], i.e. that protocol performance results should not be specific to the scenario used in the experiment. While this approach provides a general-purpose evaluation of MANET performance across a continuum of scenarios, these scenarios lack realism and have not led to development of a ubiquitous solution for MANET networking. [4] and [5] argue that successful MANET solutions can be found when they are designed to support a set of specific applications in a specialized network. It is our goal to characterize a specialized Airborne Network with realistic scenarios and to identify a working solution that may not address all possible concerns but could provide communication functionality that is currently unavailable. To manage the study, the problem space is limited to a realistic number of nodes with mobility and connectivity modeled as accurately as possible

A network consisting of military widebody aircraft is considered in this study. The widely used random waypoint mobility models of published MANET studies define movement of a node in terms of moving between randomly chosen points, with user-defined pauses between movements. In contrast, military aircraft often fly well-defined orbits that can support fairly consistent RF connectivity within radio range. Neighbor change rate will be minimal but banking and the resulting antenna occlusion can cause perturbations of the routing path. Link outages are not as frequent as might occur in random waypoint studies, but can be long-term (order of minutes) due to lack of radio range or short-term (order of seconds) due to banking. With only one radio link and a sparse number of nodes, there are no opportunities to re-route when out of radio range. Differences among MANET protocol performance in these conditions are identified.

3. MANET Models in OPNET

Identification of Standard MANET protocols has been pursued by the IETF, in particular the IETF Mobile Ad-hoc NETwork (MANET) Working Group [6], since 1996. This Working Group has been chartered to develop two standards track routing protocol specifications, one for a Reactive MANET Protocol and one for a Proactive MANET protocol. Reactive protocols discover routing paths only when traffic demands it, and as a result, when there are route changes, trade off longer packet delays in the interest of lower protocol overhead. Proactive protocols maintain and regularly update full sets of routing information, with a tradeoff of greater protocol overhead in the interest of smaller packet delays.

Despite years of research, no Internet Standards for MANET protocols have yet been specified. However, since 2003, several Experimental RFCs have been identified. Experimental status indicates that there are unanswered questions in implementing or deploying the protocol but identifies them as a technology for experimenting that might develop into standards-track protocol. Specifications for two of the MANET protocols in this study, Ad-hoc On-Demand Distance Vector (AODV)[7], and Optimized Link State Routing Protocol (OLSR)[8], have been released as Experimental RFCs.

The OPNET [9] v 12.0 simulation tool is used for this study. Multiple MANET protocols have been implemented in OPNET and previous work detailed in [10] has validated an OPNET antenna model that reflects aircraft banking effects. The protocols under study in the M&S effort include the reactive protocols, AODV, and Temporally Ordered Routing Algorithm (TORA)[11] and the proactive protocols, OLSR and OSPFv3 with MANET extensions [12].

Each protocol has specific mechanisms to provide routing, including neighbor discovery, route discovery, and route maintenance which includes response to route/link failures as well as route/link restorations. These mechanisms need to be efficient in terms of time to minimize packet delay, as well as efficient in terms of bandwidth usage, to maximize available RF resources for data. Summaries of each protocol's mechanisms, as implemented in OPNET, follow.

Reactive (On-Demand)Protocols

The reactive protocols discover routes only when traffic needs to be routed and do not identify routes within the entire network. In general reactive protocols may have larger end-to-end delays but require less overhead since they do not require network-wide information.

AODV

AODV is implemented in OPNET according to the Experimental RFC 3561. [7]

Neighbor/Route Discovery: AODV does not focus on learning about all reachable neighbors, but only those neighbors that are useful in order to transmit the data. When data needs to be transmitted to a new destination, a Route Request (RREQ) is broadcast within a specified area, initially set at 1 hop. With each failed Route Request, the broadcast area is increased. When the RREQ reaches a node that has information to the required destination, it responds with a Route Reply message. When a route fails, a Route Error is sent from the node that has noted the failed link and a new RREQ is initiated.

Route Maintenance: Active routes in AODV are maintained via periodic Hello messages; the OPNET implementation uses Hello messages at a default frequency of 1 sec, as defined in RFC 3561. If a Hello from an active node is not received within 2 seconds, the route is considered unreachable, a Route Error message is broadcast to all nodes, and another series of Route Requests are broadcast. Although only active routes can be used to forward data packets, the route table can also store invalid routes (previously valid route information) for an extended period of time. These invalid routes can provide information for route repairs and for future RREQ messages and could expedite route repairs. The lifetime of invalid routes is bounded by a 15 second timer, after which a route that is marked invalid is deleted.

TORA

TORA can operate in either On-Demand or Proactive mode. The default OPNET setting and the one used in this study, is On-Demand mode. TORA[11] specifies the routing mechanism and uses the Internet MANET Encapsulation Protocol (IMEP) [13] for monitoring link status. As with AODV, TORA routers do not maintain routes to every node in the network.

Neighbor/Route Discovery IMEP handles neighbor discovery through Beacons, with responding Echo or ACK packets confirming bidirectional connectivity. IMEP also supports Multipoint Relays but these are not implemented in OPNET. TORA broadcasts a Query message when traffic needs to be transmitted and there is no known route to the destination. Update packets are returned to the source by an intermediate node with a route to the destination.

Route Maintenance TORA can provide multiple routes to a destination and minimizes protocol overhead by localizing reaction to topological changes when possible. Changes in link status are determined by periodic IMEP Beacon/Echo/ACK packets used for neighbor discovery. A Beacon message without a replying Echo or ACK identifies a route failure and triggers another round of Query messages. Although TORA/IMEP incorporates periodic link status Beacon packets, the default timers in OPNET are large and the frequency does not impact the overhead.

ProactiveProtocols

Proactive protocols are designed to maintain knowledge of routes to all nodes in a MANET. In general, this results in higher overhead but lower end-to-end delay.

OLSR

OLSR is implemented according to Experimental RFC 3626. [8]

Neighbor/Route Discovery: Periodic HELLO messages are used to establish neighbor links and to distribute MultiPoint Relays (MPRs), determined by algorithm.

Route Maintenance: Hello messages track link connectivity. Topology Control (TC) messages, distributed by MPRs, propagate link state information throughout the network, and are broadcast periodically as well as when there is a change to the topology. Control traffic consists of periodic hellos and TC messages. Overhead is controlled by MPR broadcast and redistribution of TC messages throughout the network, rather than broadcasts of link state from each router.

OSPFv3-MANET.

OPNET implements a December 2005 Internet draft version of OSPFv3 with MANET extensions [12].

Neighbor/Route Discovery: Hello messages are used for neighbor discovery. MANET Designated Routers (MDRs) are chosen based on 2-hop neighbor information learned from Hellos and are distributed in subsequent Hello messages.

Route Maintenance: As in OLSR, Hello messages track link connectivity. If a Hello has not been received within 6 seconds, the link is declared down and a new

Link State Advertisement is distributed. Database Description and Link State Advertisements (LSAs) are distributed by MDRs to share the network's complete picture. OSPFv3-MANET uses MANET Designated Routers (MDRs) to control overhead, similar to OLSR's use of MPRs. A range of overhead control is available in the choice of LSAFullness parameter. LSA flooding can range from minimal flooding by MDRs only, to full LSA flooding by all routers, similar to that of the OSPFv2 protocol. The default setting of LSAFullness, which is implemented in OPNET, calls for full LSA flooding from MDRs and minimal LSAs from other routers.

Table 4.4 lists the pertinent MANET timers, as implemented in OPNET, that can affect performance results. A protocol's ability to recognize link outages or link restorations is controlled by these timers and their effects can be seen in Packet Delivery Ratio metric. TORA/IMEP's beacon timer is the largest timer and indicates that this protocol will not be able to recognize link outages as quickly as the other protocols. AODV's short timer should provide the fastest reaction to link outages.

Table 4.4: OPNET MANET Protocol Timer Settings (sec)

MANET protocol	Route/Neighbor Discovery	Identification of Link/Route Change
AODV	Route Request Route Reply Hello for active nodes (1 sec)	No Hello within 2 sec
TORA/IMEP	Query Message Update Message IMEP Beacon (20 sec) and responding Echo	No IMEP Beacon within 60 sec
OLSR	Hello (2 sec) Topology Control (5 sec)	No Hello within 6 seconds
OSPFv3 MANET	Hello (2 sec) LSA Distribution as needed	No hello within 6 seconds

Protocol overhead is determined largely by the periodic messages. Table 4.5 lists each protocol's control messages and their sizes. It is clear that OSPFv3MANET control messages will consume more bandwidth than the control messages of the other protocols.

Table 4.5 MANET Overhead Messages

MANET protocol	
AODV	Route Requests (24 bytes), Route Replies (20 bytes), Route Errors (20 bytes). **Periodic Messages** Hello messages (4-6 bytes) broadcast by nodes on an active route to confirm continued connectivity.
TORA/IMEP	Query (8 bytes), Update (36 bytes) messages when traffic is to be sent. **Periodic Messages** IMEP Beacon message (3 bytes) IMEP Responding Echo (4 bytes + 4 bytes per address) or ACK (4 bytes + 4 bytes per ACK)
OLSR	**Periodic Messages** Hello (8 bytes + 4 bytes for each neighbor interface) Topology Control (4 bytes + 4 bytes per advertised neighbor)
OSPFv3 MANET	**Periodic Messages** Hello (36 bytes + 4 bytes per neighbor) Router-LSAs (20 bytes + 40 bytes per neighbor)

4. SIMULATION SETUP

As noted previously, it is important to realistically model air mobility characteristics, including distances between nodes resulting from aircraft speeds and intermittent outages. This study models radio range effects and outages resulting from antenna occlusion while banking.

The scenario used for this study consists of a representative laydown of 5 widebody aircraft and a land-based Tactical Operations Center (TOC), applied to the Caspian Sea Scenario over an area of 750 n mi x 350 n mi. Each aircraft's flight path is specified by a center point and a rounded rectangle about this center point. The specifics of the rounded rectangle flight path include length, width, and radius of the circle used at the corners. In addition, the aircraft movement is defined by the speed, direction and the rotation of the pattern around the centerpoint of the node. In all simulations, each aircraft flew in a counter-clockwise direction at a speed of 400 knots at altitudes of approximately 20,000 ft. The rounded rectangle flight paths were 20 n mi wide and 110-145 n mi in length with banking angle set at 30 degrees for each aircraft. The position in which each aircraft begins its trajectory is determined by a random seed value applied to the simulation. Fifteen random seed values were chosen. The random seeds determine distances between aircraft and possibilities for connectivity.

Each aircraft was represented by a typical widebody with a tactical common data link (TCDL) antenna attached. In order to accurately model the banking effects, an OPNET model of a TCDL radio link with behavior that reflects antenna occlusion during banking that had been previously been validated [10] against live exercises was used. The OPNET model includes modifications to the OPNET 802.11 MAC layer to disable RTS/CTS. The OPNET TCDL antenna gain pipeline stages were also modified to include aircraft attitude data in calculations of the antenna pointing direction and the resulting antenna gain. The radio power was set to 200 watts power and the data rate at 10 Mbps, as noted for the TCDL link in JEFX02 exercises [14]. Point to point links are set up between each node.

A variety of simulation cases with various numbers of nodes were used within this scenario, ranging from 2 nodes to all 6. The scenario cases are listed in Table 4.1.

Table 4.1: Simulated Cases

Case	**Scenario Nodes**	**Traffic**	
		Src	**Dest**
2A	AC1, TOC	AC1	TOC
2B	AC1, AC4	AC1	AC4
3	AC1, TOC, AC4	AC1	AC4
6	All (AC1, AC2, AC3, AC4, AC5, TOC)	AC1	AC4

Traffic from source to destination in all cases was set to 1 KB UDP packets with 10 packets sent per second for a net bandwidth usage of 80 kbps. The goal was to provide a constant stream of traffic that would not generate congestion effects in this study but would require routing throughout the simulation. To ensure that initialization of the protocols had been completed, traffic was not started until 200 seconds into the simulation, and metric collection began at that point. Each simulation was run for a total of 5400 seconds, which corresponds to 2 flight path rotations for each trajectory.

Metrics collected to evaluate MANET performance include:

- Packet Delivery Ratio (PDR): The ratio of the number of data packets received to the number of data packets transmitted;
- End-to-End Delay: The time needed to deliver a packet from the data source to the data destination;
- Routing Overhead: The total amount of routing protocol traffic transmitted during the simulation.

Averages for each metric were calculated over the last 5200 seconds of each simulation run, allowing the first 200 seconds time for the protocols to initialize and stabilize.

5. SIMULATION RESULTS

The varying starting points result in different distances between nodes (and different amounts of time for radio range) as well as different times for banking (and potential link outages) for each run. MANET protocol performance results are presented in the simulation statistics in Figures 5.1-5.3. The figure for each metric displays the average value as a symbol identified in the legend, and the range of the average value, which varied with seed value, is represented by the extended lines from the symbols.

Figure 5.1 displays the average Packet Delivery Ratio (PDR), i.e. the ratio of packets received to packets sent. As can be seen, when there are few nodes and limited connectivity, as in the 2a, 2b, and 3 node scenarios, the specific protocol has little effect and PDR is unacceptable, no more than 40%. This emphasizes the lack of connectivity between these nodes, irrespective of the starting position. TORA’s PDR is the smallest, reflecting the effects of the slow timers that identify link outages.

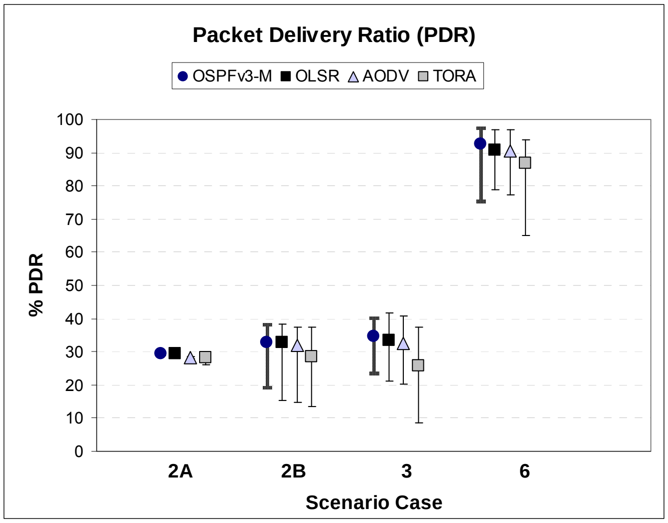

Figure 5.1 MANET Protocol Performance: Packet Delivery Ratio

Case 2A, one mobile node transmitting to a fixed node, has a minimal range of PDR. No matter where the mobile node starts on the trajectory, there is a single contiguous period of connectivity due to range between the source and destination, with no advantage for any of the MANET protocols. There is connectivity only about 30% of the time.

Cases 2B and 3, involving a mobile source node and a mobile destination node, shows more variation in PDR, due to the varying locations of the mobile nodes. The amount of time when both nodes are within radio range depends on the scenario seed, and can be seen by the variation of PDR. The least optimal starting positions result in only 12-19% PDR depending on the protocol. The difference between OSPFv3MANET, OLSR, and AODV protocols performance in PDR is not statistically significant. TORA begins to show the effects of its longer timers in Case 3 with the lowest PDR values.

The advantage of greater node density is apparent in the 6 node case, with an average PDR, in the 85-90% range for all protocols. Some seed values set starting positions in which the performance is significantly worse at 65-79% PDR. OSPFv3-MANET, OLSR and AODV have comparable performance but TORA's PDR is the lowest, again reflecting the 20 second Beacon Messages which limit its agility in reacting to changing link conditions. Although it would be reasonable to expect that the reactive AODV protocol would have a lower PDR, AODV's storage of invalid routes for 15 seconds to be used for repairs of Route Errors allows its performance to match the proactive results.

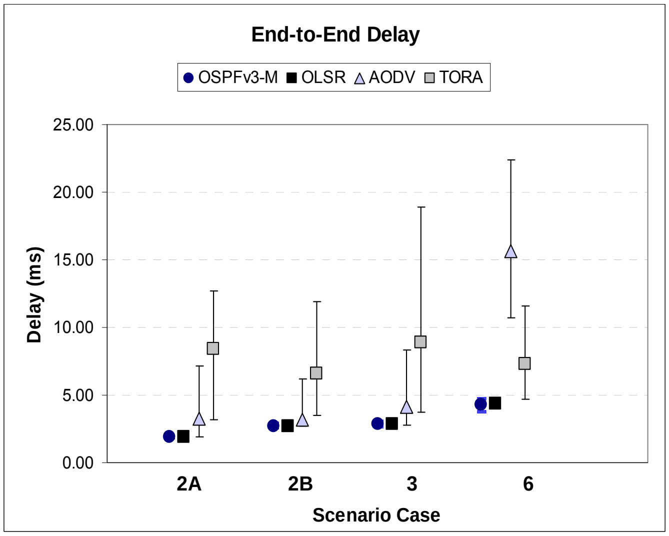

Figure 5.2 MANET Protocol Performance: End-to-End Delay

Figure 5.2 displays the average end-to-end delay for each of the MANET protocols in the different scenario cases. In general, as the number of nodes in the scenario increases, the delay increases, but the proactive protocols, OSPFv3-MANET and OLSR, show the least increase in latency with number of nodes. The proactive protocols also show the least variation among the various seed values due to their maintenance of network routing. These protocols would be useful for time-sensitive applications.

As expected, the reactive protocols result in longer end-to-end delays reflecting the delay in finding a route to the destination, when the traffic demands it. In addition, the range of delay depending on the scenario starting position is highly variable.

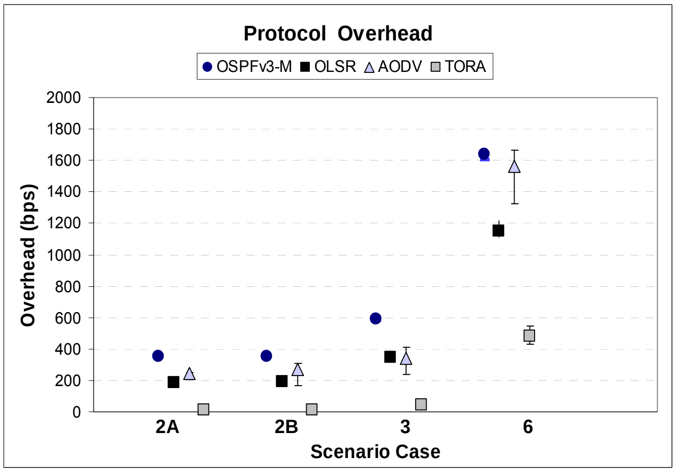

Figure 5.3 MANET Protocol Performance: Routing Overhead Traffic

The routing protocol overhead shown in Figure 5.3 shows a sharp increase in overhead traffic as the number of nodes increase for all protocols. The proactive protocols, OSPFv3 and OLSR, have the least variation in protocol overhead, which consists of periodic Hello messages that track link connectivity and link state messages that maintain routing. OLSR overhead is less than that of OSPFv3-MANET due to the larger packet sizes for OSPFv3-MANET's Hello and Link State Advertisement packets.

Of all the protocols, TORA requires the least overhead reflecting the 20 second timers for Beacon messages as compared to the 1 and 2 second Hello messages for the other protocols tested.

Overall, OSPFv3-MANET and OLSR provided the best performance results, with high PDR and consistent low end-to-end delays. In terms of protocol overhead, OLSR shows some advantage. To further confirm these advantages, OSPFv3-MANET and OLSR need to be studied in extended scenarios that include additional radio links on each node and more extensive traffic. It is reasonable to presume that in addition to a Line Of Sight (LOS) link, aircraft would be equipped with a Beyond Line Of Sight (BLOS) link. It is also important to include additional traffic flows among nodes as well since [15]] demonstrated that increased load in a network can incapacitate MANET protocol performance.

6. CONCLUSIONS and FUTURE PLANS

These results provide a baseline performance evaluation of MANET protocols for a widebody aircraft scenario with a single minimal traffic source and limited stresses of aeronautic dynamics. The proactive protocols provide more consistent performance in terms of delay, which makes them more appropriate for real time applications. In addition, the overhead costs of proactive protocols are also more consistent which can help in planning network load. It remains to be seen if these protocols provide an advantage when the scenario becomes more complex with additional radio link(s), traffic and nodes. This will be the focus of our future work.

Future work will need to examine performance when a BLOS link for the aircraft is added. It is clear that complete connectivity for an airborne network will require this for coverage and it is important to understand the impact of a longer-latency link on routing. It remains an area of future study to identify MANET protocol performance in the presence of LOS and BLOS links. It will be necessary to study which protocol can switch to an alternate link most efficiently and to identify parameters that govern the switchover.

Efforts to ensure the model and scenario are realistically portrayed will continue. As additional live flight data becomes available, calibration of models against actual results will improve the realism of the models for future simulations. More extensive simulations involving at least dozens of aircraft are needed to understand the scalability of the MANET protocols in an Airborne environment. Performance metrics obtained from a minimal scenario does not expose potential issues to be faced in a larger scenario.

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