

A Mesh Architecture for Robust Packet Delivery in Airborne Networks

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ABSTRACT

As a special subset of ad hoc networks, airborne networks aim to provide efficient network access for airborne and ground assets in a tactical environment. Conventional ad hoc routing protocols face some difficulties in such networks. First, significant overhead may be generated due to the high node mobility and dramatic topology changes. Second, temporary link failure may abort the delivery of a packet in some intermediate router.

In this thesis, we propose a cluster-based reactive routing protocol to alleviate these problems. Our solution takes advantage of mesh routers installed in unmanned aerial vehicles or aircraft capable of hovering, when such airborne assets are available. As those mesh points usually have relatively stable connections among themselves, they play the role of cluster heads, forming a hierarchical routing structure. A simple self-organizing rule is introduced in cluster management to limit the cluster control overhead and route discovery flooding. In addition, a disruption tolerant mechanism (DTM) is deployed in the routing protocol to increase resilience to temporary link or node failure. The DTM utilizes the location, bearing and speed information provided by each node and intelligently maintains a buffer of packets that cannot be immediately delivered. If a temporary link failure occurs in the intermediate router during delivery, the packet is then buffered in that router up to a maximum time-to-live. The DTM also keeps track of link changes and tries to deliver the message as soon as a new path toward the destination is found. If the buffered messages are about to time out and the destination is still unreachable, the DTM still makes an effort to deliver the packet to another router with higher probability of eventually reaching the destination.

This thesis also presents an implementation of the proposed solution in the ns-2 network simulator. The conventional Ad hoc On-Demand Distance Vector (AODV) routing protocol is adopted as the base model in the implementation. A mesh router model is programmed with two wireless interfaces. One of the interfaces is utilized to exchange routing information and packets with cluster members; the other is used to communicate with other mesh routers. This model is then installed on top of the AODV routing protocol and forms the hierarchical routing structure. The traditional AODV messages, including RREQ, RREP and HELLO, and routing tables are modified to support additional location information. Finally, the DTM is programmed and added to the AODV buffer management.

The objective of this research is to use a mesh structure and DTM to improve the reliability and performance of airborne networks. The metrics of throughput and routing overhead are taken into consideration. The simulation results demonstrate that the proposed solution satisfies our research objectives. It achieves better performance than the conventional AODV, but introduces little overhead. The mesh structure can effectively adapt to high mobility, dynamic topology and different routing capabilities. The DTM provides a sophisticated way to maintain the buffer and mitigates the impact of intermittent links.

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Chapter 1. Introduction

1.1 Research Motivation

Airborne networks are communication networks consisting of both airborne assets and ground nodes. Due to limited reliance on existing infrastructure, they can be considered a special type of ad hoc networks; they can also be classified as “opportunistic networks.”

Airborne networks tend to exhibit high heterogeneity. Battle planes and interceptors, for example, exhibit high mobility and aircraft maneuvers may cause links to periodically go down due to antenna misalignment. Airborne networks are often characterized by the presence of such *intermittent links*. Participation of this type of aircraft in the network will cause dramatic changes in topology and temporary link failures. Other aircraft, such as Unmanned Aerial Vehicles (UAVs) and helicopters, have much lower speed and can hover around a specific area. Handheld radios employed by ground assets have even lower mobility, and are constrained by limited battery life.

Although conventional ad hoc routing protocols are designed for mobile nodes, they are not necessarily suitable for airborne nodes because of high-speed mobility and frequent link interruptions. An effective and efficient routing protocol for airborne networks must adapt to high mobility, dynamic topology and different routing capabilities. The purpose of this research is to alleviate the impact of intermittent links in airborne networks, and improve the network reliability and performance.

1.2 Research Objectives

The prevalence of intermittent links in airborne networks makes the probability of failure in packet delivery high when using traditional ad hoc routing protocols. An appropriate routing architecture can alleviate the impact of intermittent links and improve network reliability. In this thesis, we propose a routing mechanism for airborne networks that can:

- Handle rapid topology changes and tolerate intermittent links;
- Improve routing robustness and network reliability; and

- Introduce little overhead.

The following tasks are pursued to demonstrate the feasibility and evaluate the performance of the proposed routing solution:

- Implement the solution in the ns-2; and
- Conduct simulations and analyze results.

1.3 Research Summary

The impact of episodic link failures on routing is modeled and simulated. Then, a cluster-based reactive routing protocol is presented to alleviate the impact of intermittent links in airborne networks. The solution takes the advantage of a mesh structure, location information and disruption tolerant network techniques. The design of our proposed solution is presented, and then implemented in ns-2. The simulation illustrates that our design satisfies the research objectives. The use of a mesh structure and disruption tolerant techniques improve the reliability and performance of airborne networks.

1.4 Thesis Organization

This thesis contains six chapters.

Chapter 2 begins by discussing conventional ad hoc routing techniques. Then, the special properties of airborne networks are pointed out, and related prior work in designing an effective and efficient airborne network is reviewed.

Chapter 3 discusses the effect of intermittent links on the routing of flows in an airborne network, which motivates us to build a mesh topology and to incorporate disruption tolerant networking mechanisms in our routing solution.

Chapter 4 describes the proposed routing protocol for airborne networks. The components of this solution are presented, including the mesh establishment and maintenance, route discovery, packet delivery and disruption tolerant mechanism.

Chapter 5 simulates the proposed solution in ns-2 and analyzes its performance. Discussions of throughput, routing protocol overhead, node density and mesh density impacts are presented.

Chapter 6 summarizes the research results and contributions. We also outline some opportunities for future work.

Chapter 2. Background

To better understand the research presented herein, a working knowledge of ad hoc routing techniques and special properties of airborne networks is required. This chapter first introduces traditional ad hoc routing protocols and highlights their characteristics. It then discusses the airborne network, including its scenarios, special routing properties and concerns. Finally, this chapter reviews the related work in the field of routing protocols for airborne networks.

2.1 Ad Hoc Routing Techniques

Ad hoc networks are self-organizing, self-healing networks. Every node in these networks has the ability to sense and discover nearby nodes, choose an optimal route for relaying packets, and heal link outages. Routing, an important element in ad hoc networks, has received much attention from the research community. The paper in [1] is a good survey of existing routing protocols. There are dozens of ad hoc routing protocols at present, and they can be classified into three primary families: proactive, reactive and hybrid.

Nodes in networks employing proactive routing protocols monitor the entire network topology by periodically exchanging control messages. As a result, routes can be predetermined and ready for use, reducing route discovery delay. However, the update control messages consume additional bandwidth, and the overhead can be significant when nodes are fast-moving and the topology changes drastically. Also, continuously tracking and updating routing information increases power consumption. This can be a problem for power-constrained nodes. Another drawback of proactive protocols is poor scalability. Because of the volume of control messages, proactive routing in large, highly dynamic networks is usually infeasible.

Reactive, also called on-demand, routing protocols take a different approach. Such protocols detect the optimal route as needed. An apparent merit of this technique is power and bandwidth saving through reduced number of control messages. The price is to introduce more route discovery delay, which can create a bottleneck in real-time communications. To find a new route, a node generally uses a flooding search. Such a

technique will consume significant bandwidth in fast-changing networks and may cause a scalability problem. Reactive routing is also vulnerable to denial-of-service attacks [2].

Hybrid routing protocols combine features of both proactive and reactive routing. The key idea of this technique is to use proactive methods for destination nodes that are nearby, while using reactive methods for route discovery to far-away destinations. Thus, hybrid routing has the potential for high scalability. Most hybrid protocols are zone-based. That means the network is partitioned into zones, within which routing is performed proactively. The overall performance largely depends on how to appropriately determine zone boundaries.

2.2 Airborne Networks

2.2.1 Airborne Network Scenarios

At least two distinct scenarios for airborne networks merit consideration. The first one is the air-to-air scenario. In this scenario, the network is completely composed of aircraft as illustrated in Figure 2-1. Since some nodes exhibit high speed, the network topology may change significantly. Therefore, rapid routing discovery and convergence are of particular interest in this kind of networks, whereas power consumption is not critical.

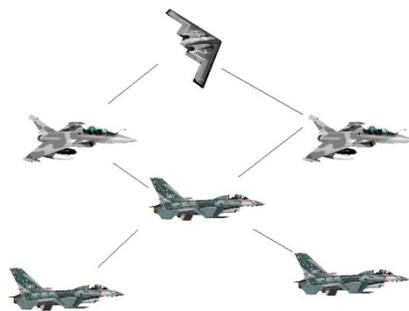


Figure 2-1 Air-to-air scenario

Another scenario of interest is air-to-ground. One example of this scenario is a network created for search-and-rescue operations, as shown in Figure 2-2. Such networks usually comprise many different kinds of nodes. Fixed-wing aircraft move very fast. In contrast, helicopters as well as ground troops are, comparatively, slow-moving nodes. Some nodes, such as hand-held radios, are energy-constrained, while others have replenishable energy

sources. Because of the complexity of this scenario, it is difficult to find an existing routing protocol that can adapt well to such different conditions. If scalability is also important, a hierarchical structure can be adopted to improve performance [2].

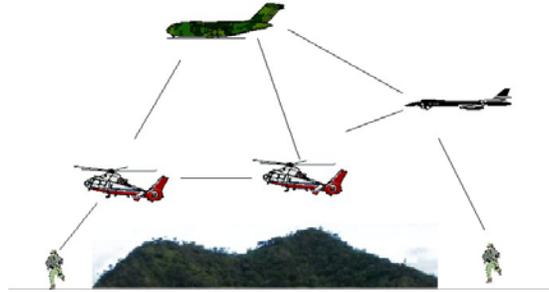


Figure 2-2 Air-to-ground scenario

2.2.2 Intermittent Connectivity Property

In airborne networks, links will undergo intermittent outages due to aircraft maneuver, such as pitch, yaw, and roll. As a result, the network topology and radio link quality vary dramatically with time. Traditional ad hoc routing protocols face difficulties in dealing with intermittent links. During packet delivery, a node stands a good chance of losing connectivity to its neighbor when forwarding packets, which usually results in packet loss. This situation is even worse in large-diameter multi-hop networks, where intermittent connectivity will trigger frequent route discovery. The next chapter presents a simulation study and discussion of the impact of intermittent connectivity. In this thesis, we also propose solutions to increase robustness of the network to such frequent route changes.

2.2.3 Location Awareness

Another common property of nodes in airborne networks is location-awareness. Using geographic location information can improve routing performance. Many ad hoc routing protocols utilize such information, including Distance Routing Effect Algorithm for Mobility (DREAM), Location-Aided Routing protocol (LAR), Zone-Based Hierarchical Link State Routing (ZHLS), and Greedy Perimeter Stateless Routing (GPSR) [1]. To support different kinds of nodes, such as satellites, aircraft, handheld radios, etc., a

hierarchical structure can be used to make the solution more scalable. The US Army's Near-Term Digital Radio (NTDR) network [2] is a good example of using such a hierarchical approach. In air-to-ground airborne networks, some nodes are energy-constrained. Therefore, power consumption also needs to be considered when designing a routing protocol. For example, in NTDR networks, these power-constrained nodes can be cluster members but are not involved in any routing operations.

2.3 Related Prior Work

Research in designing an effective and efficient airborne network is reported in [2 - 8]. Most of these papers focus on a general framework for airborne networks, including an architecture and connection management for such networks. A few of those papers look into the use of existing routing protocols, developed for generic wired or wireless networks, in airborne networks. What is still missing, however, is a routing protocol tailored to the particular needs of airborne networks. The work in [3] outlines the major components necessary to establish an airborne network. The authors of [4] examine the performance of Open Shortest Path First (OSPF) and Extended Internet Gateway Routing Protocol (EIGPR) in free space optical communications. However, the properties of optical communications are quite different from those of radio communications. In particular, an optical link can achieve very high data rates (2.5 Gbps or greater), and thus the overhead imposed by the routing algorithm is not a critical factor. In [5], the authors discuss fundamental design issues for civil aviation. The work in [6] seeks to improve the performance of OSPF in airborne networks through modifications to OSPF timer settings. However, the experiment is based on a simple 2-node network, and the scalability of OSPF in large, highly-mobile networks is still an open issue. The work in [7] characterizes the intermittent property in airborne networks. A modified OPNET model, which reflects positional antenna gain, is used in the simulation. The comparison of four traditional ad hoc routing protocols (AODV, TORA, OLSR, OSPFv3-MANET) shows that OLSR, OSPFv3-MANET and AODV have comparable performance in packet delivery ratio and end-to-end delay, while TORA exhibits the worst performance among the four protocols. The authors in [8] seek to improve network performance by incorporating disruption-tolerant mechanisms into both TCP and the link layer. The

simulation on a single lossy-link scenario shows that their solution achieves lower loss rate than traditional protocols. However, the multi-hop scenario, a more common situation in real networks, has not been considered in the work. Plus, the simulation results pertain to a particular parameterization of the transport and link layer protocols. Cross-layer optimization is still an open issue. The idea of incorporating disruption-tolerant mechanisms in airborne networks was developed independently by the authors of [8] and by us and published in the same venue [9].

2.4 Summary

This chapter describes the fundamental principles of conventional ad hoc routing techniques and introduces the characteristics and requirements of airborne networks as related to routing and packet delivery. Prior research work is then reviewed and the limitations of that research are analyzed. Traditional ad hoc routing protocols face difficulties in airborne networks due to the intermittent connectivity that characterizes these networks. As will be discussed in the following chapters, our solution alleviates this problem by incorporating a disruption tolerant mechanism and a mesh structure. The simulation results show that our proposed solution improves the reliability and performance of airborne networks.

Chapter 3. Modeling Intermittent Links

Since intermittent links often occur in airborne networks, we first investigate the impact of episodic link failures on routing.

3.1 Basic intermittent link impact

We develop a simulation model for intermittent link failures in ns-2 [13] and illustrate its use in the 5-node wireless network in Figure 3-1. Ad hoc On-Demand Distance Vector (AODV) is used as the routing protocol in the simulation. Two medium access mechanisms, IEEE 802.11 MAC and time division multiple access (TDMA), are taken into consideration.

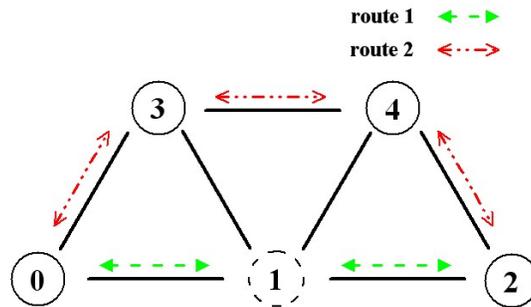


Figure 3-1 Intermittent link test scenario

The scenario illustrated here operates as follows. At time $t=0$, node 0 initiates an File Transfer Protocol (FTP) connection to node 2. AODV finds the best path along route 1, as illustrated in Figure 3-1. At $t=10.0$ seconds, node 1 goes down for an interval of 1.5 seconds. The first FTP transmission stops at $t=100$ seconds. After that, node 0 starts another FTP communication with node 2 at $t=112$ seconds.

The error control procedures of IEEE 802.11 allow the MAC layer to detect the broken link. A notification is then sent to the upper layer and a new route discovery is triggered by AODV. As a result, the data flow moves from route 1 to route 2, as depicted in Figure 3-2. AODV keeps the data flow going through route 2 even after node 1 is up again. Route 2 eventually expires after the first FTP connection is closed. In this simulation, the route expiration time is 10 seconds.

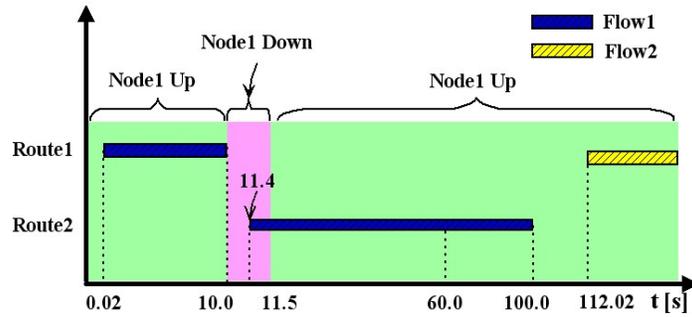


Figure 3-2 Intermittent link with IEEE 802.11 MAC

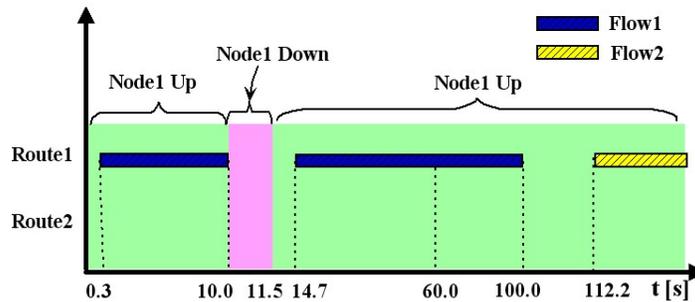


Figure 3-3 Intermittent link with TDMA MAC

A similar scenario, this time using TDMA instead of IEEE 802.11, is depicted in Figures Figure 3-3 and Figure 3-4. As MAC layer error control is not present in this case, the trigger that initiates a new route discovery is the route expiration clock: a route expires after two consecutive HELLO message losses [12], which in our case occurs at $t = 12$ seconds. If by the time the new route discovery is triggered node 1 is already up again, AODV will still select route 1 as the preferred path; this is the situation depicted in Figure 3-3. If the link-down period for node 1 is extended, route 1 is still down when the new route discovery occurs, as illustrated in Figure 3-4. As a result, AODV selects route 2 as the new route.

When the broken-link interval is small enough the intermittent link may not trigger route changes. However the transport layer may still sense the broken link, due to TCP timeout. In Figure 3-5, the node interruption is decreased to 0.4 second, and IEEE 802.11 MAC cannot sense the link failure. The result shows that TCP senses the interruption and goes into slow start (decreases its congestion window to 1).

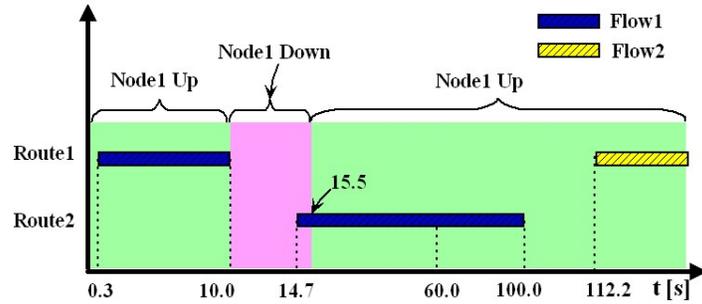


Figure 3-4 5.5-second link-down with TDMA MAC

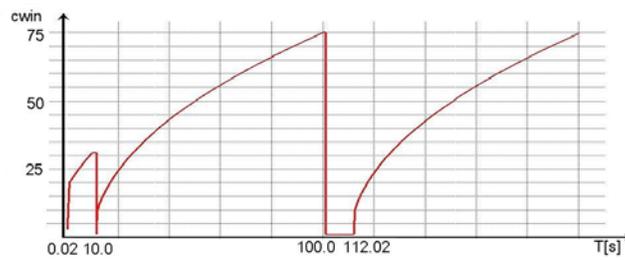


Figure 3-5 Congestion window with IEEE 802.11 MAC

3.2 Random intermittent link model

High mobility and aircraft maneuvers often result in intermittent links. To simulate such situations, we set up an intermittent link model at the physical layer in NS-2. The simulation script, then, can use two commands, *\$node disable* and *\$node enable*, to control this intermittent link, bringing the link down or up.

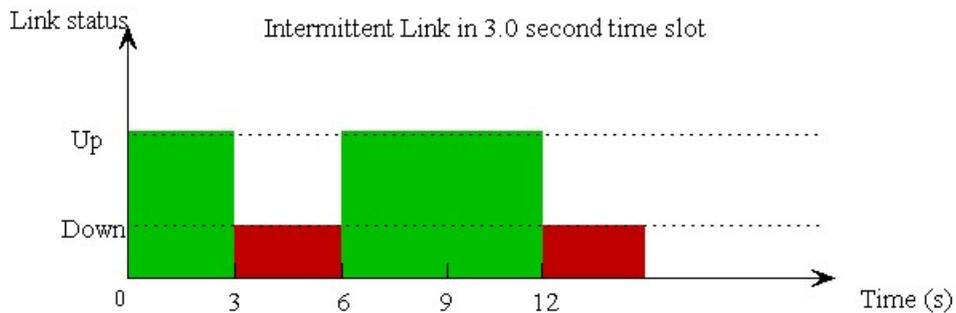


Figure 3-6 Random intermittent link model

To allow this intermittent link to be enabled and disabled for random periods of time, we divide the simulation time into fixed time slots. During a given time slot, the link will be up with some probability p , which we vary for different simulation runs. Figure 3-6 shows an example using a 3.0 second time slot.

3.3 Routing evaluation metrics

We collect three major metrics in our simulations: throughput, number of route discovery messages, and packet loss rate. Since our proposed routing protocol is based on AODV, the route discovery messages are equivalent to the RREQ messages in AODV.

- Throughput (Kbps)

Throughput is the amount of data per time unit that is delivered from the sender to the receiver.

- Route discovery messages (RREQ/node)

RREQ messages are a significant source of overhead in AODV, as well as in most other reactive protocols. They are also a good indicator that the previous route has expired and a new route is required. Since intermittent links may cause frequent route changes, observing the number of RREQ messages provides us crucial information regarding the impact of those intermittent links. Since the number of RREQ messages is also related to the number of nodes in the network, we use the number of RREQ messages per network node as the metric of interest.

- Packet loss rate

Packet loss rate is defined as: $loss = 1 - \frac{\text{number_of_packets_received}}{\text{number_of_packets_sent}}$.

This metric reflects the overall conditions of the network, including congestion, route failures, etc. It is also an important measurement of how well the routing protocol can tolerate the presence of intermittent links.

3.4 Evaluation platforms and testing parameters

Since the evaluation focuses on the impact of intermittent links, simulation scenarios need to be carefully selected. Factors other than intermittent links, such as mobility, should be isolated, because they may impair the routing performance as well. The network scale is also an important factor in the routing performance. Therefore, three different network scenarios are considered.

3.4.1 One-route scenario (3-node scenario)

This is the simplest multi-hop scenario. In this network, there is only one route between the sender and receiver. The intermediate node experiences intermittent connections to sender and receiver. As a result, the communication between sender and receiver is interrupted by this intermittent behavior.

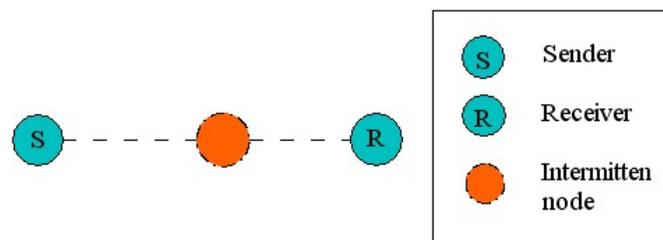


Figure 3-7 One route intermittent link scenario

3.4.2 Two-route scenario (4-node scenario)

This scenario contains 4 nodes: sender, receiver and two intermediate nodes. Like the previous scenario, each intermediate node experiences intermittent links (these periods of link disconnection for the two intermediate nodes are independent of each other). Therefore, the delivery path from sender to receiver should oscillate between the two routes.

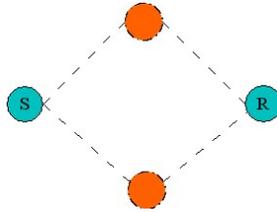


Figure 3-8 Two-route intermittent link scenario

Actually, new route discovery only occurs under three major circumstances [12]. First, the active route expires, which means the route remains idle for long enough that it is deleted from the routing table. After that, route discovery will be initiated again when a new transmission starts. Second, one of the intermediate nodes misses at least two HELLO messages from its next hop. The node considers its neighbor is no longer valid after missing two HELLO messages from that neighbor, and thus initiates a new route discovery. The third case occurs when AODV receives a broken-link message from the MAC layer. The error control procedures of IEEE 802.11 allow the MAC layer to detect a broken link: a message is then sent to the upper layer and route discovery is triggered in AODV. In the case of ns-2's TDMA model, the link layer cannot detect a broken link, and this third circumstance will never occur.

3.4.3 Multiple alternate route scenario (36-node scenario)

In this test, we consider a scenario that contains 34 intermediate nodes, and therefore multiple alternate routes when any single link fails, shown in Figure 11. As we would expect, the intermittent links have an even more significant impact in this large network.

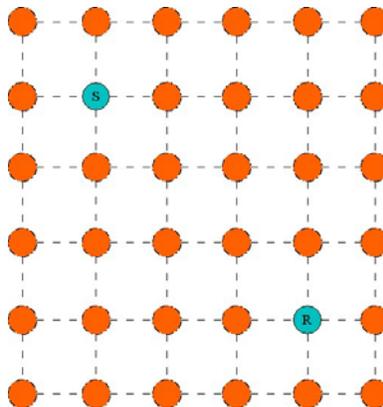


Figure 3-9 36-node scenario

For the three scenarios above, we also need to specify other parameters, related to the application layer, TCP, MAC layer, etc. Figure 3-9 illustrates all simulation scenarios we considered. At the transport layer, both TCP and UDP protocols were taken into consideration. At the MAC layer, IEEE 802.11 and TDMA were examined. In each case, both 0.5 and 3.0-second time slots were tested. Note that two HELLO intervals take 2.0 seconds. If the down period for the intermittent link is less than 2.0 seconds long, it will not trigger route discovery. We also ran some simple experiments that tested time slots of both 1.0 and 1.5 seconds. They showed similar trends as the experiments with a 0.5-second time slot. In the 36-node network scenario, only the 3.0-second time slot was considered. Therefore, there were 20 simulation scenarios in our test. Table 3-1 shows the major parameters for each simulation case.

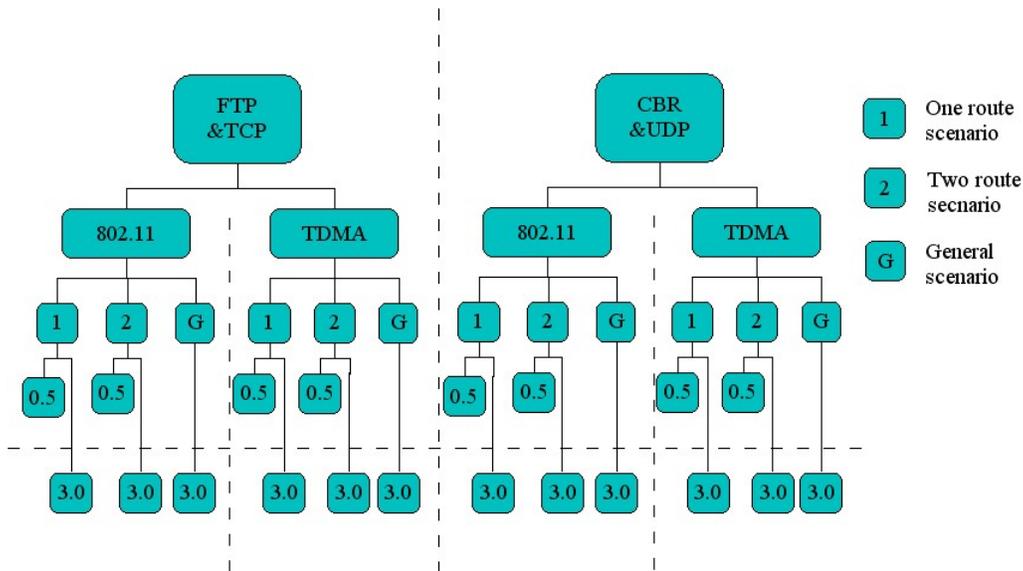


Figure 3-10 Simulation cases (20 cases)

In each case, we set intermittent link-down rate to 0.5%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50% and 55% (12 rounds). Each round simulates a transmission of 600.0 seconds.

	TCP				UDP			
	802.11		TDMA		802.11		TDMA	
	0.5	3.0	0.5	3.0	0.5	3.0	0.5	3.0
1	TCP- 80211-0.5- 1	TCP- 80211-3.0- 1	TCP- TDMA- 0.5-1	TCP- TDMA- 3.0-1	UDP - 80211-0.5- 1	UDP - 80211-3.0- 1	UDP - 80211-0.5- 1	UDP - 80211-3.0- 1
2	TCP- 80211-0.5- 2	TCP- 80211-3.0- 2	TCP- TDMA- 0.5-2	TCP- TDMA- 3.0-2	UDP - 80211-0.5- 2	UDP - 80211-3.0- 2	UDP - 80211-0.5- 2	UDP - 80211-3.0- 2
G	N/A	TCP- 80211-3.0- G	N/A	TCP- TDMA- 3.0-G	N/A	UDP - 80211-3.0- G	N/A	UDP - 80211-3.0- G

Table 3-1 Parameters for intermittent evaluation

3.5 AODV performance with random intermittent links

In this section, we examine AODV performance according to the parameters above. The results are separated into three sets: throughput, AODV RREQ messages, and packet loss. Each set contains six plots which are arranged in the order of Table 3-1.

3.5.1 Throughput

The general trend for throughput, as shown in Figure 3-11, is to decrease with the increase of the intermittent link down rate (the proportion of time that the intermittent link is down). From the left column, we can see that IEEE 802.11 has better performance than TDMA in TCP transmission, as a larger number of collisions are observed in TDMA. The last row shows that the throughput in the 36-node scenario drops dramatically as intermittent links become more pervasive.

3.5.2 AODV RREQ messages

Figure 3-12 illustrates the simulation results of RREQ overhead. The performance with TDMA MAC is quite unstable because of the large number of collisions experienced. When using the IEEE 802.11 MAC, the number of RREQ messages increases with the increase in link down-time in the first two rows. The last row in Figure 3-12 shows that the RREQ overhead increases at first and then decreases. This is due to a large number of intermittent nodes in this scenario. Network conditions keep deteriorating as the intermittent link down rate increases, and as a result, after some point even RREQ messages cannot be sent out.

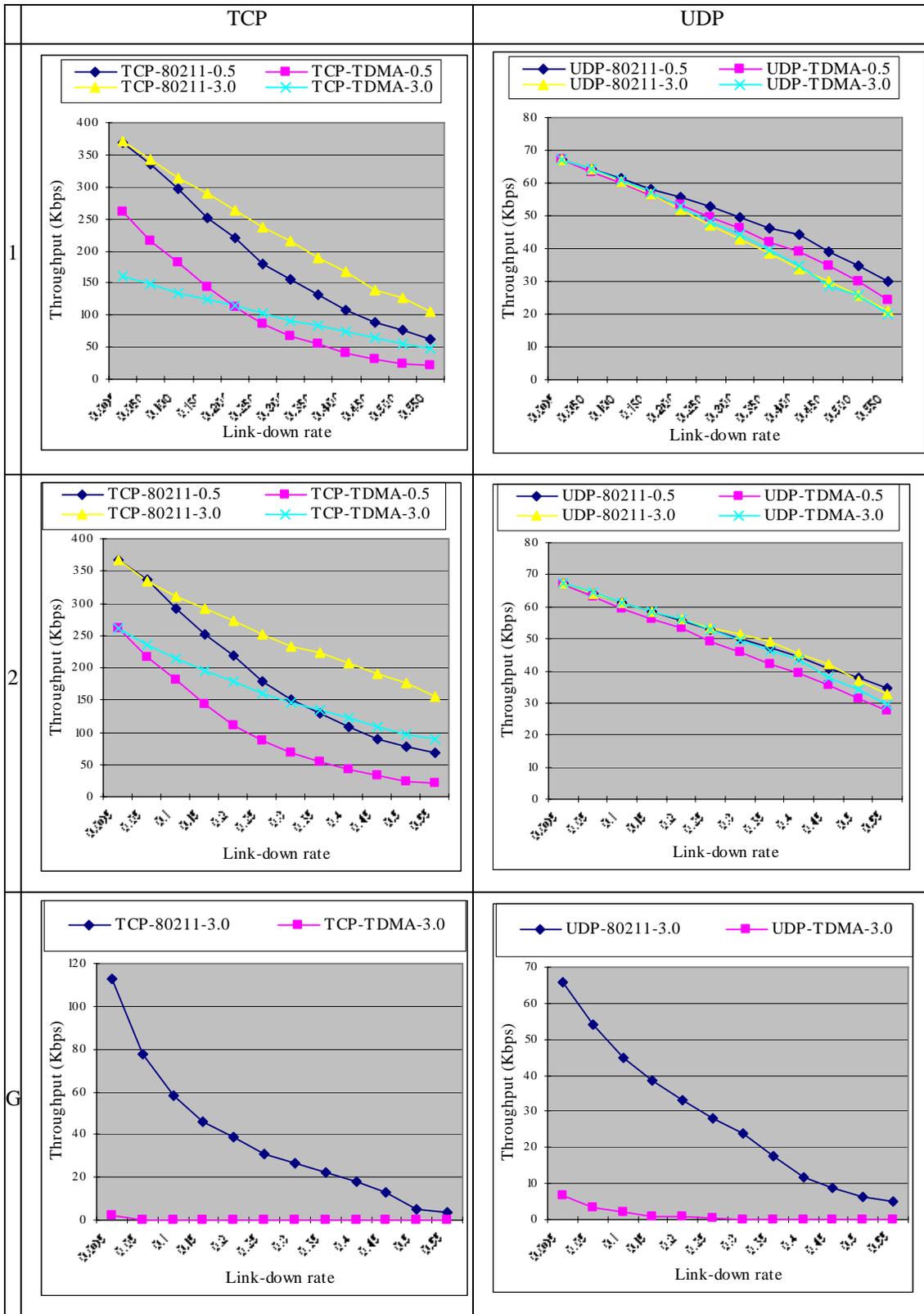


Figure 3-11 Throughput results of intermittent link tests

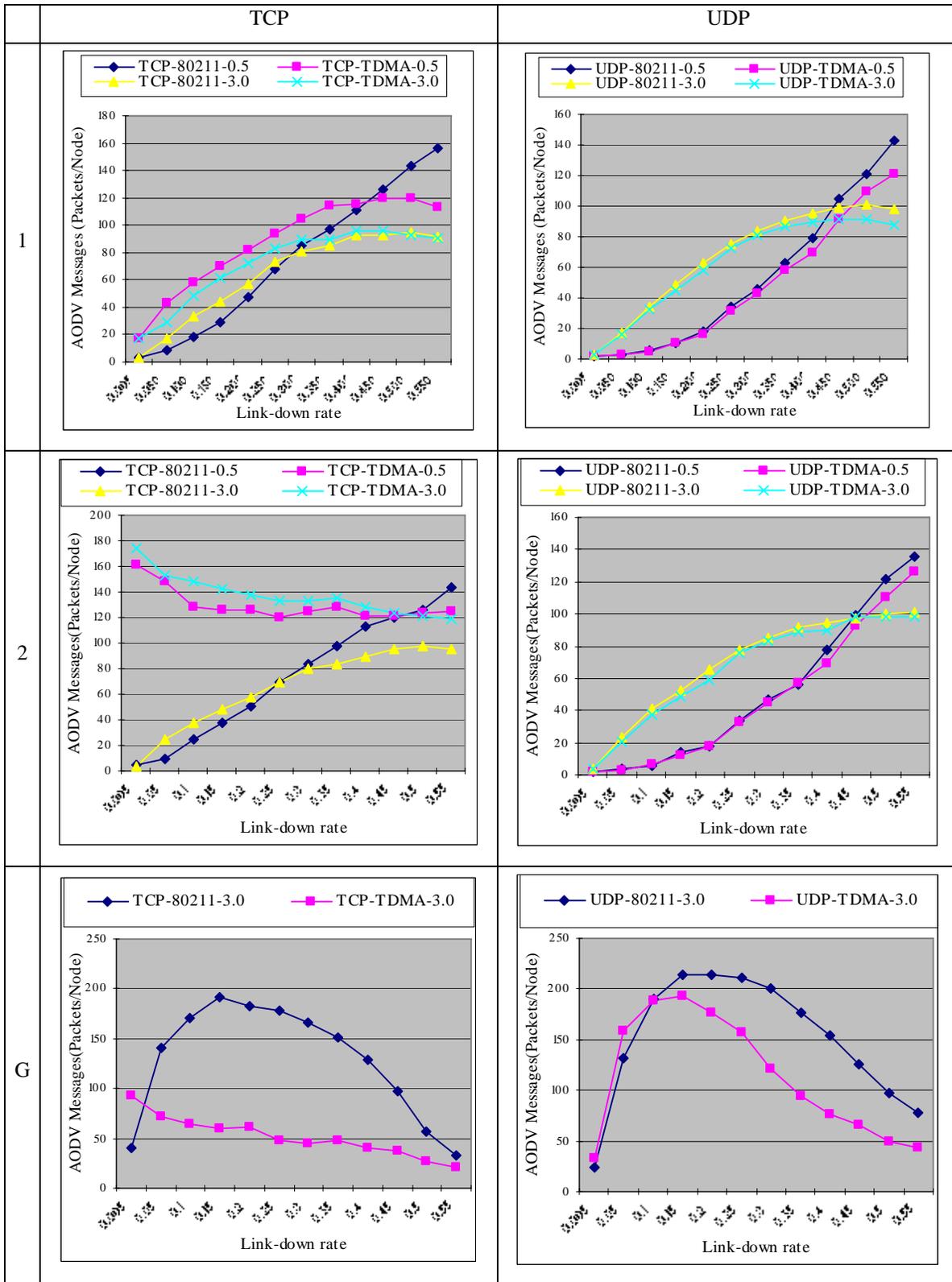


Figure 3-12 AODV message results of intermittent link tests

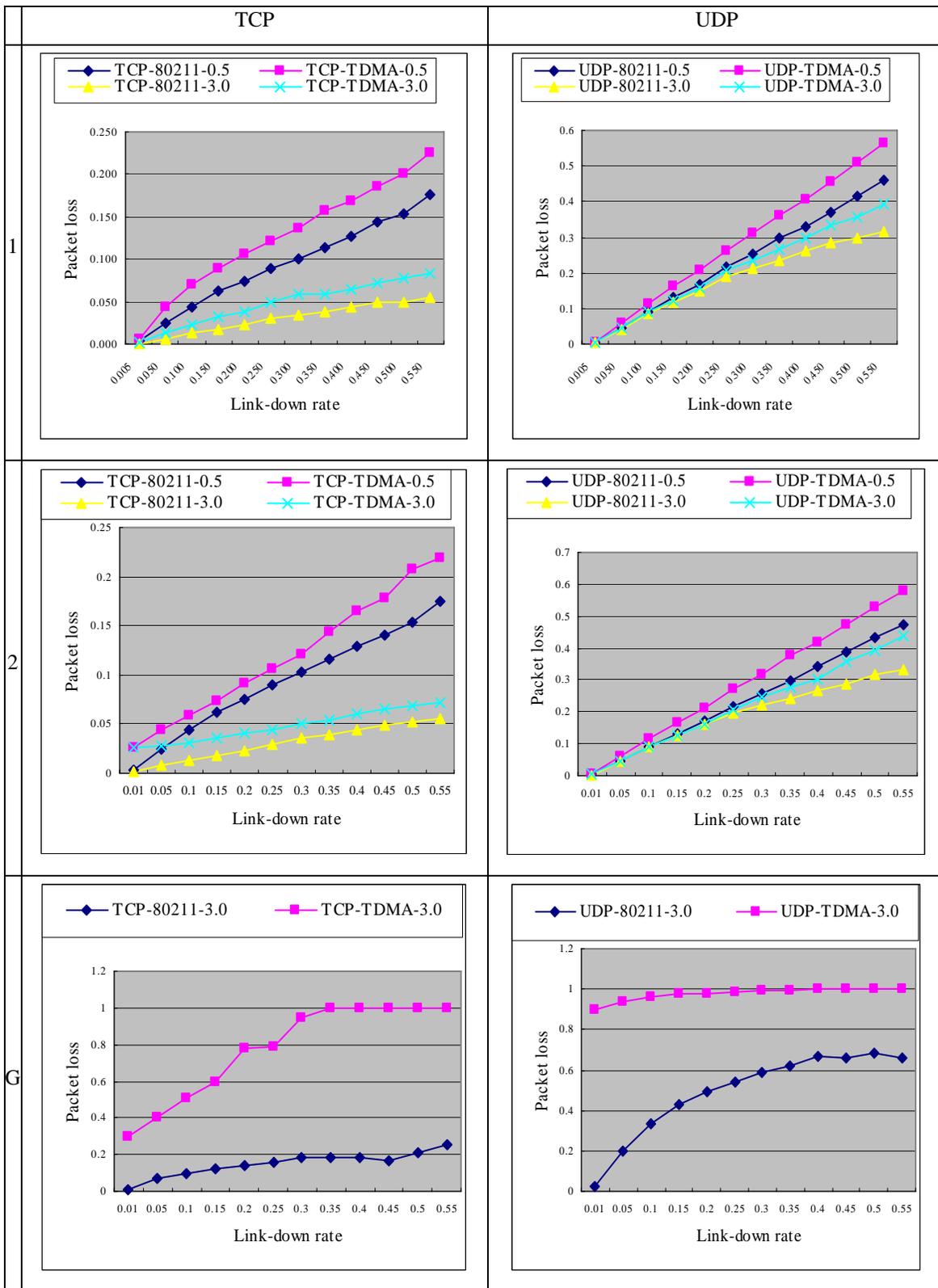


Figure 3-13 Packet loss rate results of intermittent link tests

3.5.3 Packet loss rate

Typically, UDP transmission exhibits higher loss than TCP transmission, as shown in Figure 3-13. The reason is that TCP sends out much fewer packets than UDP due to its congestion control mechanism. It is also shown that IEEE 802.11 exhibits lower packet loss than TDMA.

3.6 Summary

This chapter presents a study of the impact of intermittent links in ad hoc networks. As discussed in the previous chapter, in airborne networks links between two neighbors can become quite unstable, and this intermittent connectivity makes the network topology change dramatically with time. As illustrated by the simulation results, the throughput continually decreases when the intermittent link down rate increases, while overhead (the number of RREQ messages) and packet loss rate keep increasing. This deterioration in network performance motivates us to establish a mesh topology and to incorporate disruption tolerant networking mechanisms for airborne networks, as discussed in the following chapters.

Chapter 4. Forming a Mesh in the Sky

Conventional ad hoc routing protocols are not tailored to the requirements of airborne networks. First, significant overhead may be generated due to the high node mobility and dramatic topology changes. Second, temporary link failure may abort the delivery of a packet at an intermediate router. We have designed a cluster-based reactive routing protocol to alleviate these problems. This protocol effectively creates a mesh in the sky, and we have incorporated the use of location information and disruption tolerant network (DTN) techniques into the protocol to increase its robustness to the highly dynamic environment of an airborne network.

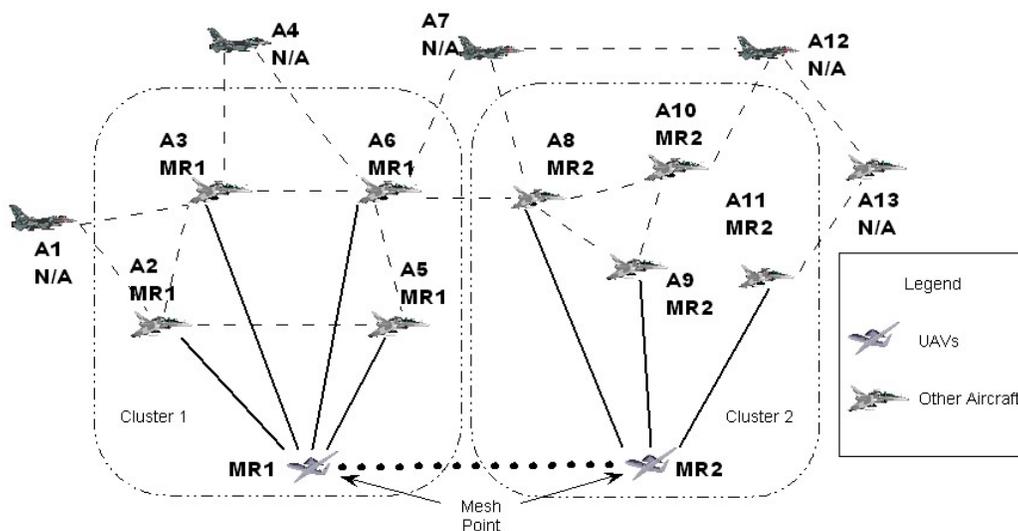


Figure 4-1 Airborne network scenario

Our objective is to efficiently find a route to deliver packets if a path exists between source and destination. The basic scenario of interest is illustrated in Figure 4-1. The solution takes advantage of mesh routers installed in UAVs or aircraft capable of hovering, when such airborne assets are available. As those mesh points usually have relatively stable connections among themselves, they play the role of cluster heads, forming a hierarchical routing structure. A simple self-organization rule is introduced in cluster management to limit the cluster control overhead and route discovery flooding.

In addition, a disruption tolerant mechanism (DTM) is deployed in the routing protocol to increase resilience to temporary link or node failure. This mechanism utilizes location information provided by each node to intelligently maintain a buffer of packets that cannot be immediately delivered, in anticipation of a route becoming available in the near future. The DTM first attempts to deliver the packet to a neighbor closer to the destination when location information is available. Otherwise, it attempts to forward the packet to a neighbor in another cluster, utilizing the stable links among mesh points, to increase the likelihood that the packet will eventually be delivered to its destination.

4.1 Motivation and Approach

The routing protocol we propose builds upon Ad hoc On-Demand Distance Vector (AODV) [12], a reactive hop-by-hop routing protocol. AODV has a flat structure and has the potential to support dynamic networks [1]. However, it may generate significant overhead and experience large delay in airborne networks due to the high node mobility and possibility of frequent link failure. An improvement is to utilize some more stable links and limit the duplicate flooding that reactive routing protocols tend to generate during route construction. Mesh networks give us a solution. First, mesh points provide relatively stable links among themselves. Second, mesh points can act as cluster heads, forming a hierarchical routing structure. The original flat network of AODV is then segmented into several clusters. Each cluster can be configured with a unique cluster ID (CID). The overhead can be further minimized by implementing hierarchical rules for route discovery. In our routing protocol, the route discovery flooding of AODV is only implemented inside a cluster. Route discovery to other clusters generally goes through the link between mesh routers. The advantage here is that duplicate route requests are limited to a certain range instead of flooding the entire network. Moreover, since mesh routers usually hover around a certain area, their locations are relatively stable. The rapid topology changes can be mitigated by using these mesh points.

4.2 Cluster Maintenance

Our routing protocol uses UAVs or other hovering aircraft as cluster heads; these are indicated as Mesh Router 1 (MR1) and Mesh Router 2 (MR2) in the example in Figure

4-1. Nodes capable of acting as mesh routers are pre-configured with a unique CID. The cluster is automatically formed and maintained by a simple self-organization rule. Each cluster head periodically broadcasts cluster control messages (CCM), the format of which is shown in Figure 4-2. The CCM contains the CID of the mesh router generating the message and also the IDs of other clusters that are known to this router; we call these associated clusters and denote the corresponding ID as the associated cluster ID (ACID). For example, since there is a direct link between MR1 and MR2, MR2 is an associated cluster to MR1, and vice versa. The objective of advertising ACIDs is to limit the route discovery flooding, as described later.

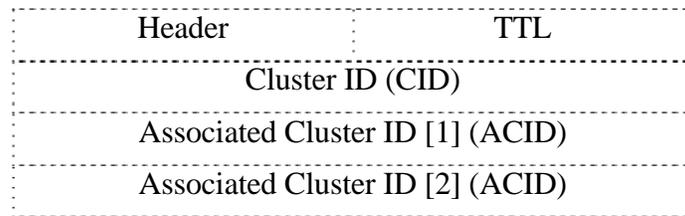


Figure 4-2 Cluster control message (CCM)

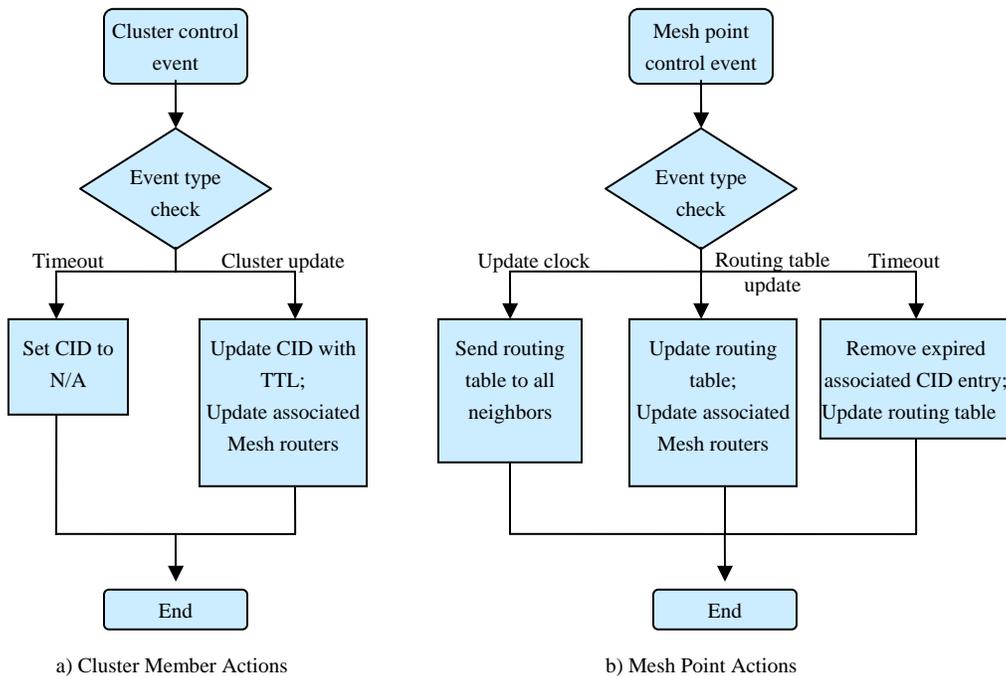


Figure 4-3 Cluster Access and Maintenance

Each node receiving CCMs will select one cluster to join. The selection rule may depend on the signal strength of the received CCMs or on other metrics. The time-to-live (TTL) field in CCMs is used to evaluate for how long this cluster information will be valid. If the CCM times out and the node does not receive any additional CCMs, it will change its CID value to N/A, which means the node does not belong to any cluster. Similarly, when a node receives a new CCM or joins a new cluster, it will update its CID and corresponding ACIDs. Note that nodes need not register with any cluster heads or advertise which cluster they decide to join. These cluster access and maintenance processes are illustrated in Figure 4-3a.

The focus of the cluster organization and maintenance procedure is on simplicity. The cluster head just needs to periodically advertise its CCM and does not need to know any information regarding its cluster members. Meanwhile, the airborne nodes, which are traveling through the cluster areas, receive CCMs (potentially from multiple cluster heads) and select one cluster to join. In the example in Figure 4-1, the dot-dashed lines represent two clusters; note that it is also possible that some nodes will not belong to any cluster.

Since mesh points are relatively location-stable in the network, proactive routing can be implemented among these nodes. Each mesh router periodically exchanges its routing table with its mesh point neighbors. The actions taken at the mesh points for such routing table updates are shown in Figure 4-3b. The routing table in mesh points is also updated when they receive a reactive route control message, as discussed later.

4.3 Route Discovery

The route discovery process we propose adopts Ad hoc On-Demand Distance Vector (AODV) as a starting point. There are four major route control messages in AODV: Route Request (RREQ) message, Route Reply (RREP) message, Route Error (RERR) message, and HELLO message. Our routing protocol uses the same types of messages as AODV.

Upon receipt of a RREQ, if the node knows of a valid route to the destination, it issues a RREP. Otherwise, the node must decide whether to forward the RREQ. In the previous

section, we mentioned that a RREQ is only flooded inside the cluster, while a cross-cluster RREQ needs to go through the link between mesh routers. For instance, taking our example in Figure 4-1, a RREQ broadcast by A6 will not be forwarded by A8, and vice versa. Now suppose that A3 initiates a route discovery with destination A10, and that the link between MR1 and MR2 is currently unavailable. The route discovery will fail, even though in this case a route does exist between A3 and A10 (namely, A3-A6-A8-A10).

To solve this problem, additional cluster information is needed. Our approach is to carry CID information in the RREQ packet to declare the cluster to which the source of the RREQ belongs. The format of our modified RREQ message is shown in Figure 4-4. When an intermediate node receives a RREQ packet, it needs to decide whether it should forward that packet. Every regular node in a particular cluster obtains its own CID and ACID information from the CCMs it receives. If a RREQ packet comes from a node in one of the associated clusters, the receiving node knows that this packet can be delivered to other members of its cluster through the mesh link. Otherwise, that packet will be forwarded by the receiving node, because the node has no sufficient evidence to know this packet can reach other members of its cluster through other routes. Note that in our previous example the route between A3 and A10 would thus be found even if the link between MR1 and MR2 is unavailable. The flowchart in Figure 4-5 summarizes the actions of an airborne node when it processes an incoming route control message. Some distinguishing features are marked by dashed circles. We also indicate where we introduce location information and DTM features into the protocol, as discussed later.

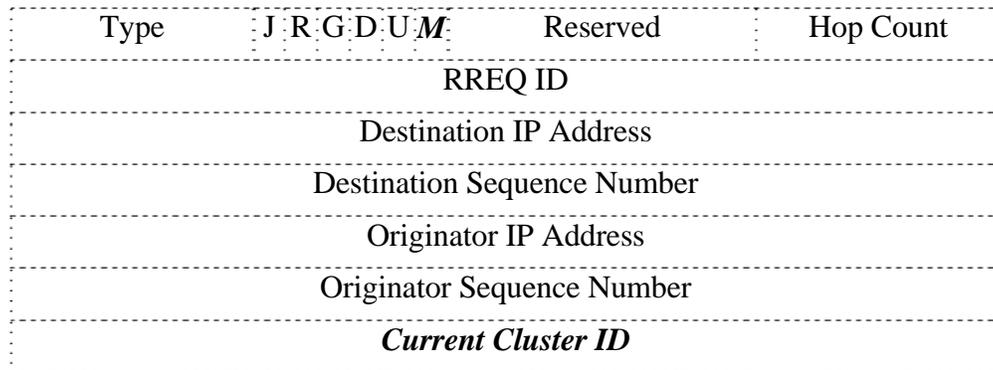


Figure 4-4 Route Request (RREQ) Message Format

When a node initiates a RREQ message, it includes its own CID information in that message. When the RREQ message arrives at the intermediate routers, they will check the CID contained in that request. If the CID is the same as that of the intermediate router, the router knows that the packet originator is in the same cluster and will forward the request to its neighbors. Otherwise, the intermediate route will additionally check whether the RREQ comes from one of the associated clusters. The node compares the CID with its own ACIDs. If there is no match, the node believes that there is no mesh point link currently available between these clusters. Thus, it will still forward the RREQ to its neighbors, because this may be the only chance for the request to reach its destination. Otherwise, i.e. if there is a match between the associated CID and the CID of the requestor, the router assumes that the request will finally get delivered to other members of its cluster via the mesh routers. The router will then discard the request. For example, A6 generates a RREQ and forwards it to its neighbors. Since A3, A5 and MR1 have the same CID as A6, they will forward this request when they receive the packet. A4 and A7 will also forward the packet because their CID and ACIDs are N/A. Whether A8 forwards this packet depends on the ACID information of A8. If cluster 1 is associated with cluster 2, A8 will get this information from CCMs and discard this request. Otherwise, A8 will forward the request on A6's behalf.

A further improvement is to utilize location information in the route control message exchange, as illustrated in Figure 4-5. Since HELLO messages have the same format as RREP, the modification in RREP will also work for HELLO messages. The location information can be obtained from higher layer applications. It generally includes 3-dimension position, as well as bearing and speed information. Each node will maintain a location table to record and update such information. By doing this, every node will be aware of the location of its neighbors and the destination node. Finally, a DTM can be incorporated when the node receives a RERR message. The RERR message is generated whenever a link failure causes one or more destinations to become temporarily unreachable. At this time, if a packet arrives at certain node, instead of discarding it, the node will buffer the packet and try to find an alternative approach to deliver it.

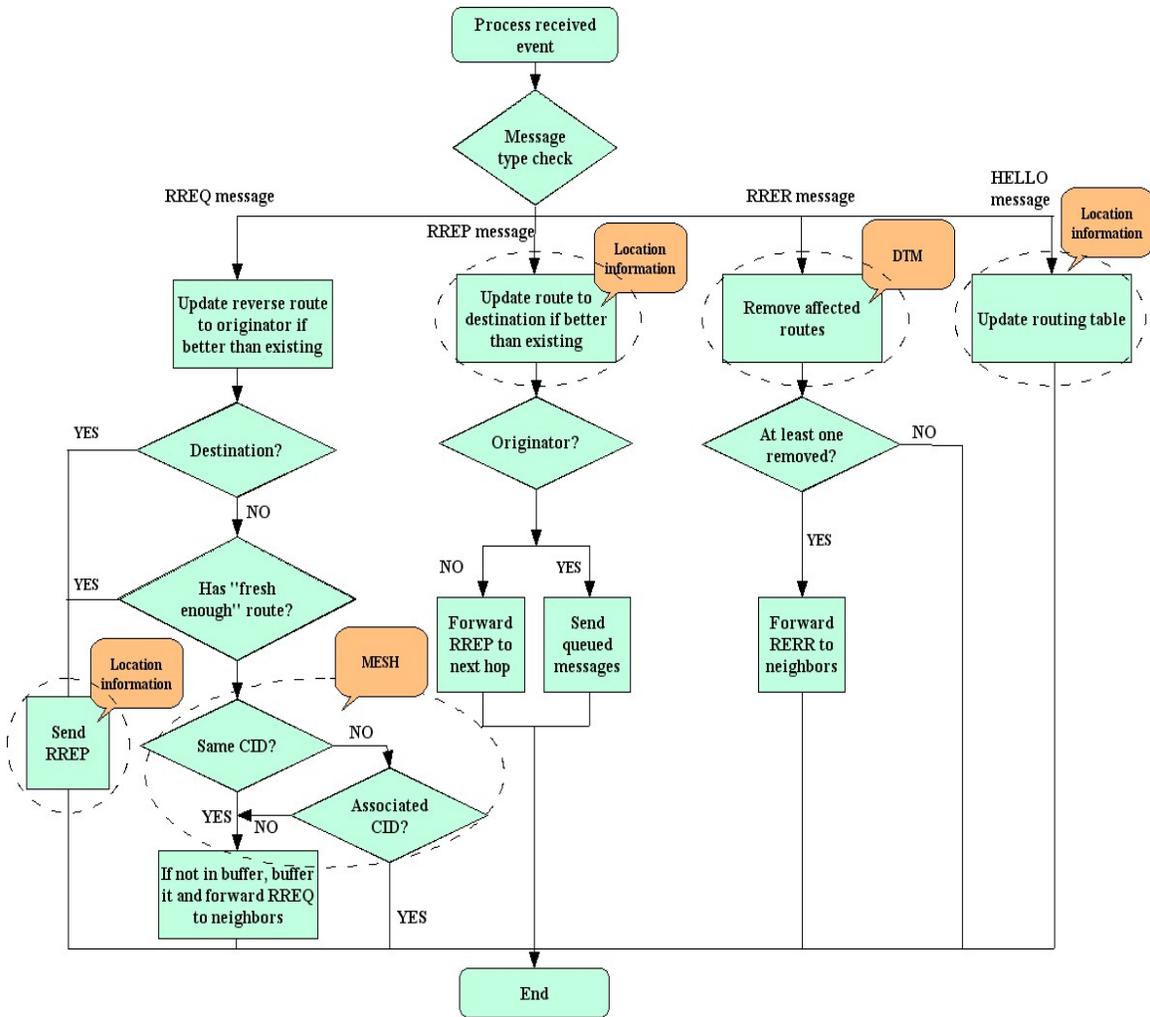


Figure 4-5 Route Control

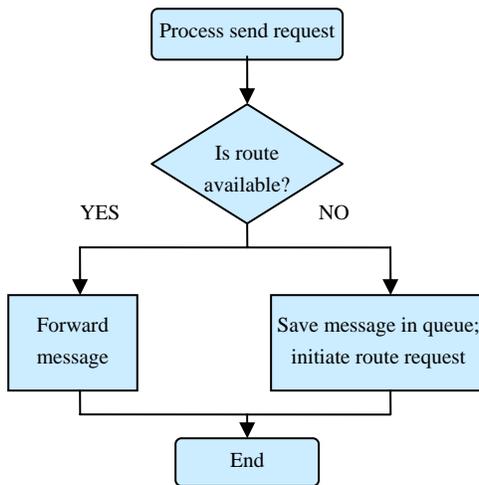


Figure 4-6 Packet Delivery

4.4 Packet Delivery

The packet delivery process is the same as in most reactive routing protocols, including AODV. If a route exists, the router simply forwards the message to the next hop. Otherwise, it saves the message in a message queue, and then it initiates a route request to determine a route. The flowchart in Figure 4-6 illustrates this process.

4.5 DTN mechanisms for ad hoc networks

Conventional ad hoc routing protocols face difficulties in networks with intermittent connectivity. The reason is that traditional ad hoc routing techniques assume there is always a connected path from source to destination. However, this assumption is not always valid in realistic scenarios, when links in the network may experience intermittent connectivity. As a result, routing performance, in particular packet loss rate, decreases dramatically, as shown in the previous chapter.

Disruption tolerant network techniques aim to provide a solution for this problem. The objective of disruption tolerant networking is simple: trying to deliver the packet to the next hop even when there is currently no path between source and destination, and by doing so increasing the likelihood that the packet eventually reaches the destination.

Some of the DTN techniques proposed in the literature require obtaining additional information from other layers in the protocol stack, including the application layer and the physical layer; others rely solely on knowledge gathered at the network (routing) layer. The performance of a DTN correlates to the complexity of the algorithm adopted. A sophisticated DTN may achieve better performance, at the cost of higher complexity. In this report, we introduce three representative classes of mechanisms that are being used in disruption tolerant networks.

4.5.1 Blind flooding

The advantage of blind flooding is its simplicity. It usually only requires periodic pairwise connectivity to ensure eventual message delivery. The idea is to increase the delivery probability by exchanging packets whenever two hosts are within radio range, which may eventually result in the delivery of the message to its intended destination.

The algorithm in [19], called Epidemic Routing protocol, is such a technique. It is illustrated in Figure 4-7. Each host maintains a buffer consisting of packets that it has originated as well as packets that it is buffering on behalf of other hosts. When two hosts (A and B) are approaching each other, host A initiates contact with host B by sending its summary vector (SV), which briefly provides information regarding its local buffered packets. B compares this information to its own summary vector and determines which packets stored remotely have not been seen by the local host. Then, B sends out a request vector to A for those packets. At the last step, A sends out packets that are requested by B. This procedure repeats until every neighbor within radio range updates its buffered packets.

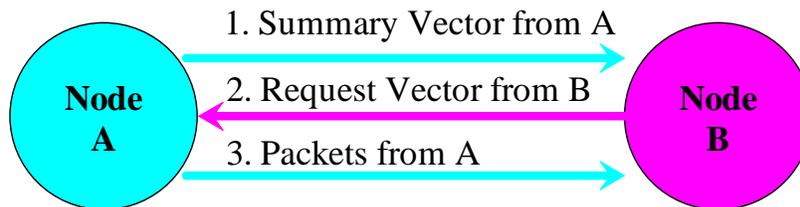


Figure 4-7 Epidemic routing protocol when two hosts, A and B, come into transmission range of each other [18]

The disadvantage is that blind flooding usually requires very large memory space to store the buffered packets, because the host will still hold that packet even after it has been delivered. Packets are only deleted from the buffer due to overflow. When the buffer reaches its capacity, the oldest packet will be deleted. Since every two hosts unconditionally exchange their packets, network security, packet duplicates and loops are also issues with this technique.

4.5.2 Reactive next-hop selecting based on neighbor's information

Reactive next-hop selecting, such as [20], attempts to mitigate the problems with blind flooding outlined above. The typical solution is to have the routing protocol take into account cross-layer factors, such as physical or MAC layer information, application support and so on, and then select the next hop with highest delivery probability based on that information. Since this is a reactive approach, the information gathering and decision making only happens when a packet needs to be delivered.

For example, the author in [20] defines a utility variable as the metric that represents the neighbor's closeness to the destination. When a packet needs to be sent, the host initiates a utility request to all its neighbors. The request includes packet destination, time to live, and the host's utility. All neighbors that receive this request calculate their own utility. The neighbor that has higher utility than the originator will reply to the request with its utility value. The originator finally selects the neighbor that has the highest utility as its next hop. The utility may have several components based on factors such as what node was most recently noticed, or most frequently noticed, or on a node's future plans, power level and so on.

The apparent advantage of such a reactive solution is saving bandwidth and memory space, compared with blind flooding. The drawback is requiring additional support beyond the network layer. Furthermore, this technique needs to consider some exceptions, such as how to make a decision if all of the neighbors have lower utility than the threshold.

4.5.3 Proactive next-hop selecting based on neighbor's information

Instead of selecting the best next hop only when it needs to deliver a packet, a proactive solution periodically exchanges delivery probability information among the hosts. PROPHET in [21] is a good example. It is based on the epidemic routing described in [19], but it aims to determine only one neighbor to exchange buffered data with, instead of sending the packets to every neighbor. The delivery probability calculation in [21] is sophisticated. It considers not only probability attenuation along each hop, but also probability aging in one host.

The advantage of the proactive approach is reducing the next-hop discovery delay. However, periodically exchanging delivery probability information may consume large amounts of bandwidth even when there is no data for delivery. Also, the probability information maintenance and updating algorithm is relatively complex.

4.6 Buffer Maintenance based on DTM

When the route discovery is initiated, our routing protocol maintains a buffer of undelivered packets incorporating some features of DTM, as shown in Figure 4-8. The DTM utilizes the location information of both neighbors and destinations. When an exception occurs during the route discovery process, such as timeout, destination unreachable or buffer overflow, the DTM will make an effort to deliver the packet to another router with higher probability of eventually reaching the destination, instead of simple discarding it. Thus, the packet with higher delivery likelihood will be sent out as soon as a route to the destination is found.

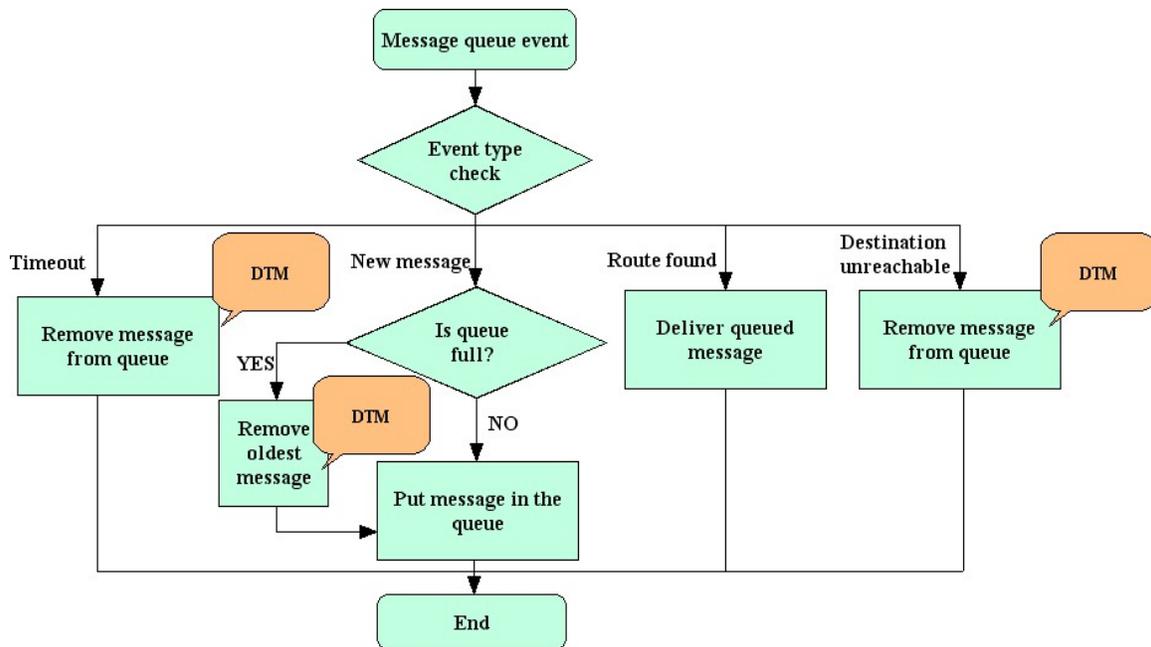


Figure 4-8 Buffer Maintenance

Several DTMs have been reviewed in the previous section. In this work, we introduce a simple but effective DTM by utilizing location information and mesh structure. When a valid packet must be sent with no route available, the DTM first attempts to deliver the packet to a neighbor closer to the destination when location information is available. Otherwise, it will try to forward the packet to a neighbor in another cluster and utilize the stable links among mesh points. The detailed DTM algorithm is shown in Figure 4-9.

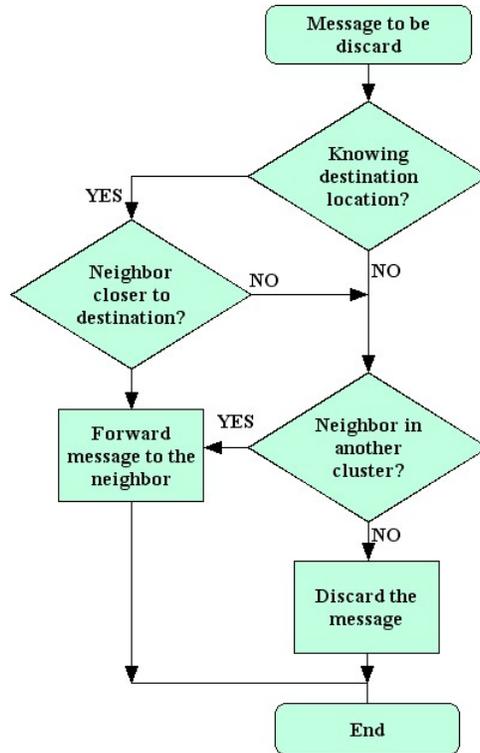


Figure 4-9 Disruption Tolerant Mechanism

4.7 Summary

In this chapter, a "mesh in the sky" solution is proposed to improve the reliability and performance of airborne networks. The solution deploys a number of mesh routers that establish stable links among themselves. Each mesh point also plays the role of cluster head, enabling a hierarchical routing structure. Finally, location information and disruption tolerant mechanisms are further integrated into the routing protocol to mitigate the impact of intermittent links in airborne networks. As described in the next chapter, our solution can be built on top of conventional ad hoc routing protocols. The ns-2 simulation shows that the mesh structure provides stable intermediate hops and achieves reliable packet delivery for airborne networks.

Chapter 5. Simulation Results and Analysis

The simulation in this thesis employs the ns-2 [13] network simulator. We first introduce some basic settings and parameters that are used to simulate airborne networks. Then, the propagation model, random mobility model and location information model are presented. After that, the mesh structure and DTM are presented to form hierarchical routing and alleviate the impact of intermittent links. The final simulation results show that our solution effectively improves the network performance.

5.1 Simulation preliminaries

The scenario we simulate attempts to replicate the scenario in Figure 4-1. Due to their low speed relative to the other nodes, mesh points that are installed in UAVs, helicopters, or other aircrafts capable of hovering, are simulated as static. All other nodes exhibit the mobility characteristics described in the next sub-section.

5.1.1 Parameters and settings

We started from a simple baseline simulation scenario, relying whenever possible on the existing components of ns-2.

➤ Propagation Model:

NS-2 supports two propagation models: FreeSpace and TwoRayGround.

FreeSpace is used in our simulation.

➤ Link (MAC) Layer Model

NS-2 supports two MAC models: IEEE 802.11 and preamble-based TDMA.

IEEE 802.11 is investigated in our simulation.

➤ Network Layer Model

Since the designed “mesh in the sky” routing protocol shares some similarities with AODV, we adopt the conventional AODV routing protocol as the base model for our simulation. The mesh and delay tolerant mechanisms proposed in the previous chapters are then added to it.

Ns-2 is an open source network simulation tool. However, there is no built-in airborne model in the current ns-2. The default mobility model in ns-2 is designed for research on

ground-based networks, such as formed among common laptops with IEEE 802.11 wireless interfaces. The typical radio range in ns-2 is 250 meters. We have had to determine the parameters that support a transmission range of 100 nautical miles (expected of airborne assets, as described in [10]), and to code this transmission range into existing ns-2 models.

The communication range in ns-2 is determined by two parameters: transmission power and receive threshold. For a given transmission, the receiver will examine the received signal power. If it is above the receive threshold, the data can be received; otherwise, the sender is considered to be out of range. The received signal power in ns-2 is calculated by the Friis propagation model. The Friis free space equation states that the received power P_r at distance d , obeys

$$P_r = \frac{G_t G_r \lambda^2}{4\pi d^2} P_t$$

where $\lambda = c/f$ is the wavelength, f is the frequency, G_t and G_r are transmit and receive antenna gain, and P_t is the transmitting power. We used a fixed transmit power of 0.281838 watt for all the simulations, and the remaining parameters were set as shown in Figure 5-1 below.

```
distance = 185200
propagation model: FreeSpace

Selected parameters:
transmit power: 0.281838
frequency: 9.14e+08
transmit antenna gain: 1
receive antenna gain: 1
system loss: 1

Receiving threshold RXThresh_ is: 5.60594e-15
```

Figure 5-1 Receive threshold for airborne network

Ns-2 uses a random waypoint model for the random node movement. Normally for large topologies, the node movement and traffic connection patterns are defined in separate files. These movement and traffic files may be generated using CMU's movement- and connection-generators. Since the transmit range parameter is also hard-coded in these generators, we needed to modify the source code and recompile it to meet the requirements of an airborne network. Part of the generated result is shown in Figure 5-2 below. First, the data specifies the initial position information of each node. Then, the destination and speed of the nodes are defined as a time event. After that, the initial distance (hop count) information is counted by a general operation director (god). Currently, the god object is used only to store an array of the shortest number of hops required to reach from one node to another, for each possible pair of nodes. The god object does not calculate this on the fly during simulation runs, since it can be quite time consuming. The information needed by the god object during the simulation is loaded from the movement pattern data.

```
# nodes: 20, speed type: 1, min speed: 340.00, max speed: 680.00
# avg speed: 490.52, pause type: 1, pause: 0.00, max x: 1000000.00, max y: 1000000.00
$node_(0) set X_ 409878.229781676084
$node_(0) set Y_ 720207.797317584511
$node_(0) set Z_ 0.000000000000
$node_(1) set X_ 909661.552451924304
$node_(1) set Y_ 125090.864025731527
$node_(1) set Z_ 0.000000000000
...
$ns_ at 0.000000000000
"$node_(0) setdest 145381.048610261205 479403.374883323442 610.211794698623"
$ns_ at 838.865467763863
"$node_(15) setdest 786552.565778357442 369233.507150916732 542.249578495490"
...
$ns_ at 125.664147561550 "$god_ set-dist 0 9 1"
$ns_ at 138.203078204516 "$god_ set-dist 6 16 2"
```

Figure 5-2 Random Mobility Generation

Finally, the ns-2 parameters for each airborne node are listed below.

- Node Speed
 - Randomly distributed between Mach 1 and Mach 2 (340 m/s to 680 m/s).
- Data Rate

64 Kbit/s UDP data rate is used in the simulation to model the exchange of voice packets. Since we set the UDP packet size to 256 bytes, the IP packet size is therefore 276 bytes which achieves a data rate of 69 Kbit/s at the network layer.

➤ Transmission Range

100 nautical miles = 185,200 m.

5.1.2 Obtaining location information for AODV in NS-2

The location information in ns-2 is stored in *Class MobileNode*, which is a core class in the wireless simulation. The general location information includes three-dimensional positions X, Y, Z and the node's speed. To utilize this information, we additionally define a *MobileNode* pointer in the *Class AODV* and attach it to the node object. Therefore, the location information can be obtained by invoking the class method:

```
inline void getLoc(double *x, double *y, double *z);
```

32 bits	32 bits	16 bits	32 bits	32 bits	32 bits	8 bits
dst	seq no.	hops	last_hop_count	nexthop	expire	flags

Figure 5-3 Conventional routing table entry in ns-2

184 bits	32 bits	32 bits	32 bits
conventional part from Figure 5-3	X	Y	Z

Figure 5-4 Routing table entry with location support in ns-2

After having the necessary location information, AODV needs to exchange this information with other nodes. Thus, the structures of routing table, RREQ, RREP and HELLO messages in AODV have to be modified so that they can support location information. The conventional routing table entry in ns-2 is shown in Figure 5-3. We place the location information at the end of the entry. The position is recorded by three double variables which are illustrated in Figure 5-4. Similar modifications are also made to RREQ, RREP and HELLO messages. The packet format of RREQ in our simulation is illustrated in Figure 5-5.

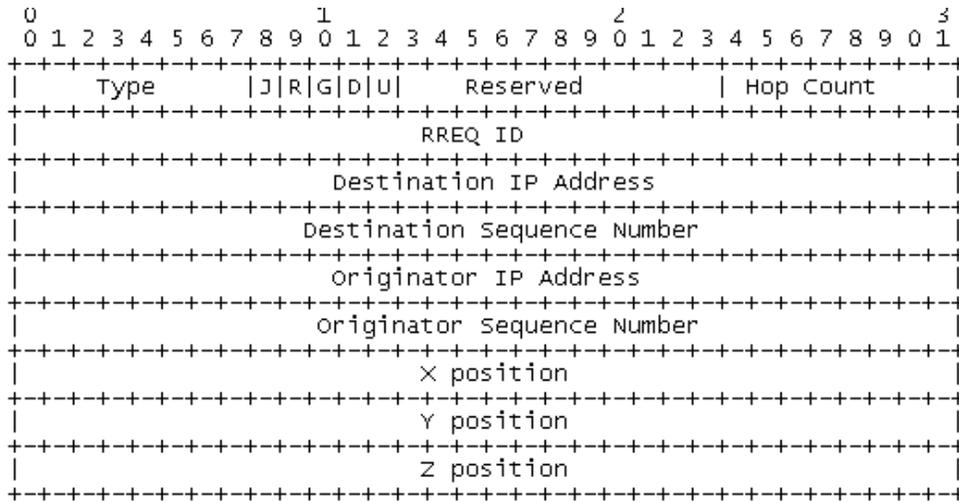


Figure 5-5 RREQ message format with location support

5.1.3 Integrating mesh structure and DTM

Since our routing protocol is based on AODV, the mesh points should also be able to deal with traditional AODV messages. The difference is that a mesh point will send out cluster control messages (CCMs) instead of HELLO messages. Mesh points periodically broadcast CCMs, the format of which is shown in Figure 5-6.

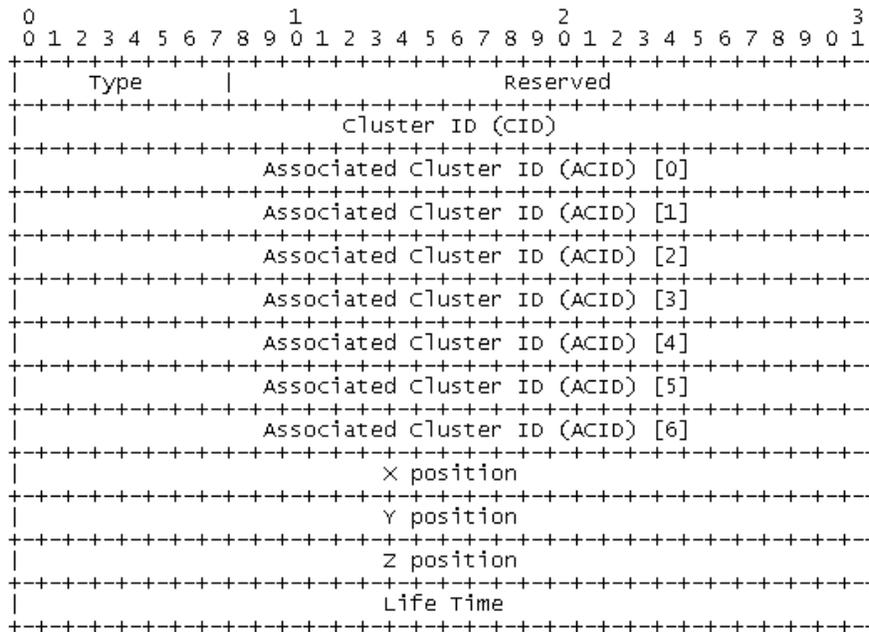


Figure 5-6 CCM format

The CCM contains the CID of the mesh router generating the message and also the IDs of other clusters that are known to this router; we call these associated clusters and denote the corresponding ID as the associated cluster ID (ACID). Each node receiving CCMs will select one cluster to join. The selection rule depends on the signal strength of the received CCMs. In addition, the mesh point typically has longer communication range than other nodes. In our simulation, the radio range of a mesh point is about 1.8 times that of common nodes. We also assume that the link between every two mesh points is stable.

➤ CCM packet format

The format of the cluster control message is illustrated above, and contains the following fields:

Type	0x20
CID	ID of the mesh point
ACID[7]	up to 7 IDs that are associated with the mesh point
X,Y,Z	Location information
LifeTime	the valid period for this packet

➤ CCM actions in mesh point

The mesh point performs two primary actions involving CCMs. First, CCMs, instead of HELLO messages, are sent out every second. In fact, the CCM carries all the information that a HELLO message has. Therefore, a node receiving a CCM can also treat the mesh point as one of its neighbors. Second, ACID and neighbor lists are updated when receiving a new CCM from other mesh points.

➤ CCM actions in cluster member

A cluster member can select and join a cluster when it receives a CCM. If the node receives multiple CCMs, it will join the cluster with the best signal strength. Cluster members also track and update their own cluster information. If the node senses that a better mesh point appears or the current cluster expires, it will update its CID variable and ACID list.

➤ Disruption tolerant mechanism

The implementation of DTM is based on the algorithm in section 4.6. The DTM procedure will be invoked in one of the following cases (in those cases, the packet would have been dropped in the original AODV):

- ◆ Link layer detection feedback;
- ◆ Failure to find a route for the received packet;
- ◆ Expiration of a valid route;
- ◆ Reception of RERR error messages; or
- ◆ Rout request retries that exceed the parameter RREQ_RETRIES.

In order to tolerate a certain degree of delay, we also increase the buffer size in AODV from 64 packets to 1024 packets.

5.2 Mesh and DTM evaluation

After installing the mesh and DTM models into the ns-2, we initiate, in this section, a performance evaluation and analysis of our proposed solution. First, a basic network of 24-node is deployed in the ns-2, shown in Figure 5-7. This network runs the traditional AODV routing protocol without mesh points. The 24 nodes are randomly distributed in an area of 460 nm \times 380 nm, and experience intermittent connectivity. Node 23 is selected to be the sender while node 18 is the receiver.

Starting from the network in Figure 5-7, two mesh points are then deployed to cover the area, as depicted in Figure 5-8. The blue circles in the figure show the coverage area of the cluster. The objective of the simulation is to evaluate the effects of the mesh structure and to compare the performance of networks with and without mesh points. Two metrics, throughput and routing overhead, are taken into consideration. For each intermittent link down rate in Figure 5-9 and Figure 5-10, 10 rounds are simulated and the results presented below represent the average of those 10 repetitions. As the standard deviation of the 10 simulation rounds is very small, we have confidence that 10 samples are sufficient for our results. Some other parameters are listed in Table 5-1 below.

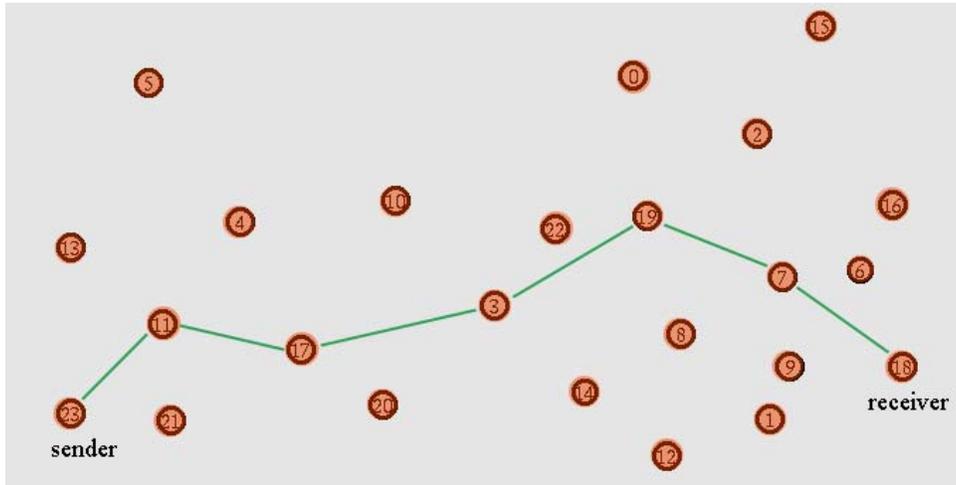


Figure 5-7 24-node network without mesh

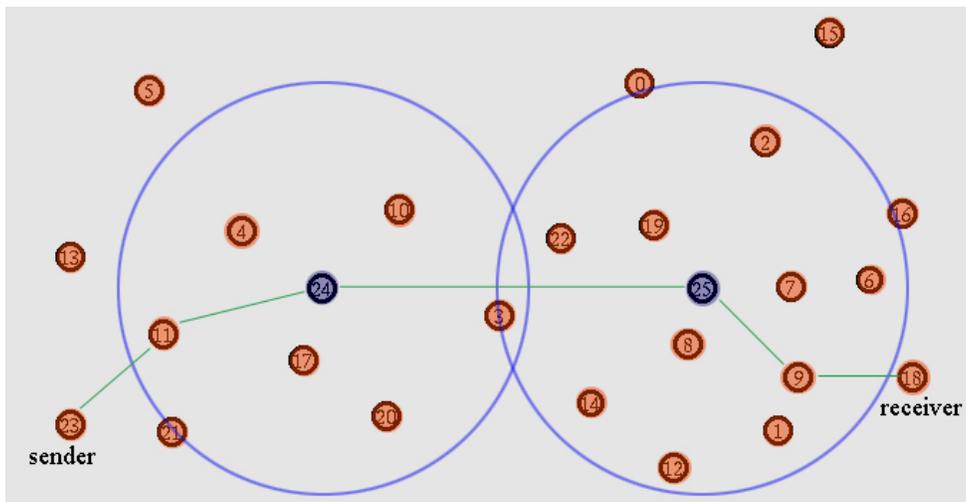


Figure 5-8 24-node network with two mesh points

Transport Layer Protocol	TCP/UDP
MAC Layer Protocol	IEEE 802.11
Intermittent Time Slot	3.0 seconds
Intermittent Rate	0.5%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50% and 55%
Transmission Time	600 seconds
Number of repetitions	10 samples for each intermittent rate

Table 5-1 Parameters for mesh and DTM evaluation

5.2.1 Throughput

The general trend for throughput is to decrease with the increase of the intermittent link down rate. We can see from Figure 5-9 that mesh structure helps the network performance. The DTM further improves the performance. Actually, the mesh performance would be even better if both sender and receiver were inside the clusters, because in that case they would have direct connections to their respective mesh points. Since DTM may introduce extra delay to the packet delivery, the TCP may time out before the packet reaches the destination. Therefore, DTM performs even better in UDP than in TCP.

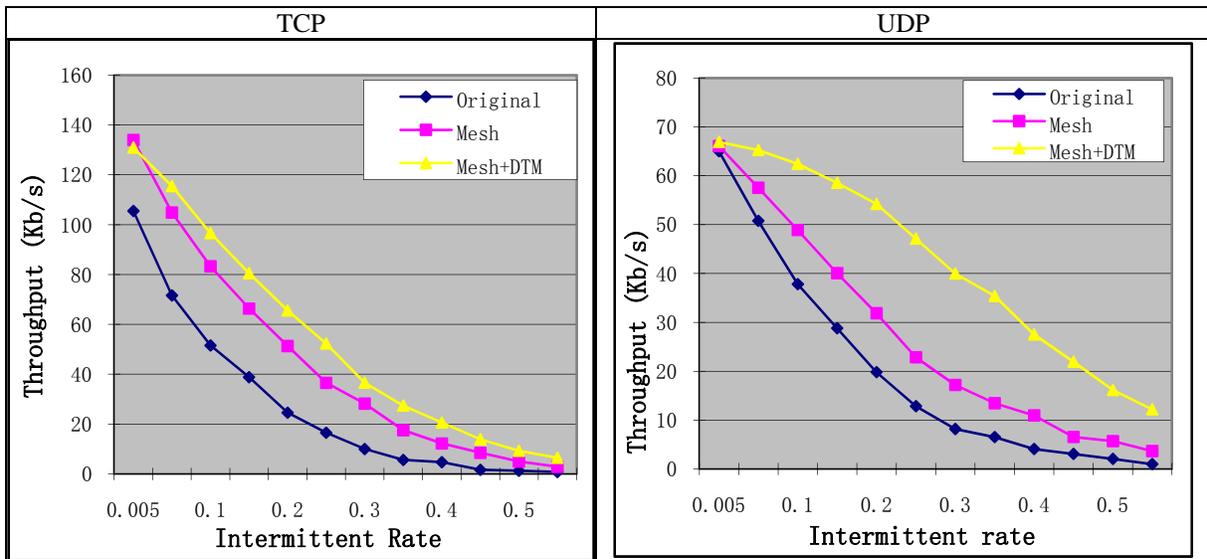


Figure 5-9 Throughput

5.2.2 Routing protocol messages

Figure 5-10 illustrates that the number of RREQ packets increases at first and then decreases as we increase the intermittent rate of links. As discussed in section 3.5.2, this is due to the deterioration of network conditions. As the intermittent link down rate increases after a certain point, even RREQ messages cannot be sent out. We also observe that the number of RREQ messages in the mesh network is almost the same as for the non-mesh network during the increasing period and slightly larger during the decreasing period. Actually, the mesh structure provides stable links among mesh points, which increases the probability that a RREQ message reaches more clusters far away. As a

result, more RREQ messages are forwarded through the stable intermediate hops of mesh points, as the intermittent rate increases.

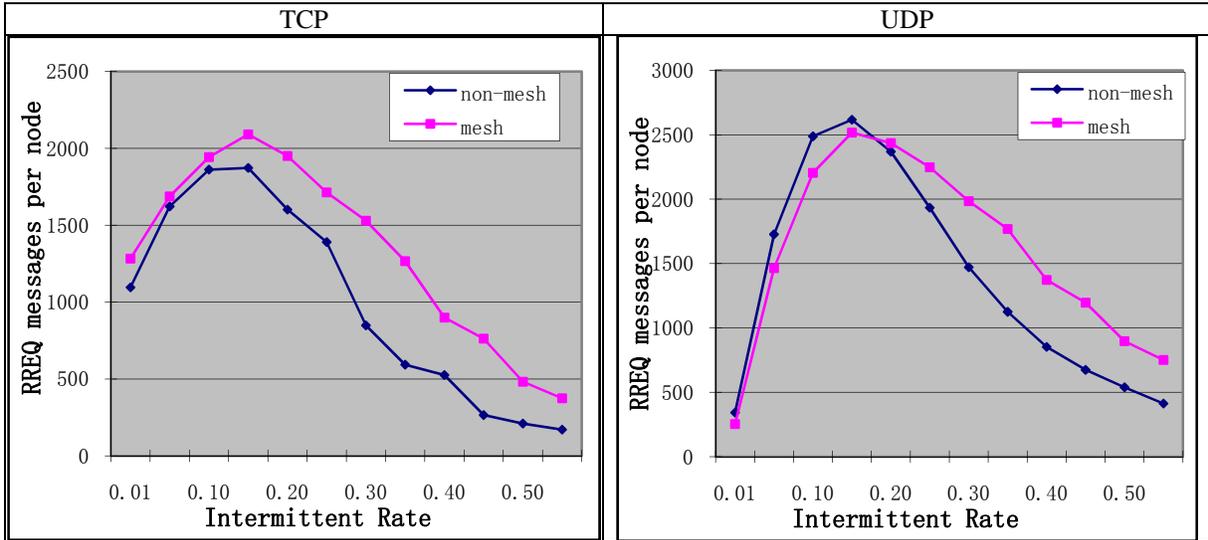


Figure 5-10 AODV RREQ messages per node

5.2.1 Random pair analysis

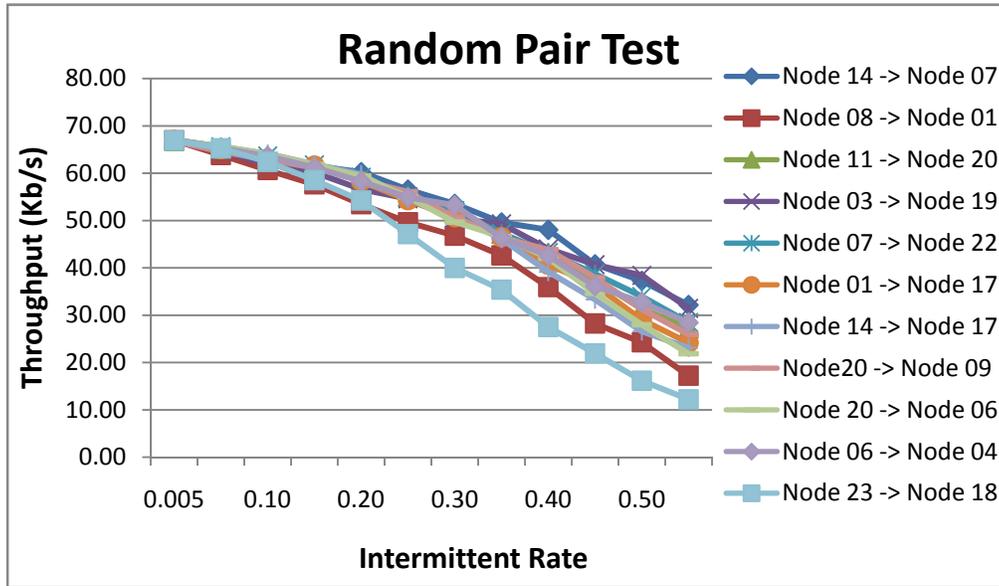


Figure 5-11 Throughput of random pair test

The simulation in Figure 5-8 selects node 23 and node 18 as the sender and receiver, the results of which illustrate that our mesh and DTM solution effectively improves the performance of airborne networks. In this section, we further verify that this solution can

benefit every node inside the mesh, and the improvement can apply to any pair of nodes in the network. 10 different pairs are randomly selected from Figure 5-8 to be the sender and receiver. For each pair, a similar UDP transmission as in section 5.2.1 is simulated with different intermittent rate. The result in Figure 5-11 shows that the 10 random pairs have similar performances and trends as section 5.2.1. Therefore, the mesh structure and DTM are applicable to all nodes in the network.

5.3 Node density analysis

We have examined the effectiveness of mesh structure in airborne networks so far. However, how to efficiently deploy the mesh points is still an open issue. In this section, we first examine the relationship between node density and network performance. In the next section, we further investigate the relationship between mesh density and network performance.

The node density can be measured by the number of regular nodes in a particular area. Since a network, with a fixed mesh structure, has limited bandwidth and capacity, it would achieve different performance with the different node density in the area. Part of the simulation parameters are listed below:

- Simulation area: 1000 nm × 1000 nm, an area that would roughly cover half of the continental United States, as illustrated in Figure 5-12;
- Radio range of regular nodes: 100 nm;
- Radio range of mesh points: 180 nm;
- Mesh structure: 42 mesh points are uniformly distributed in advance and form a fixed mesh network, depicted in Figure 5-13. Since the radio range between two connected mesh points is 180 nm, 42 mesh points, therefore, are enough to cover the entire simulation area.
- Number of replications of each simulation: each point in Figure 5-14 is based on 100 independent simulation rounds.

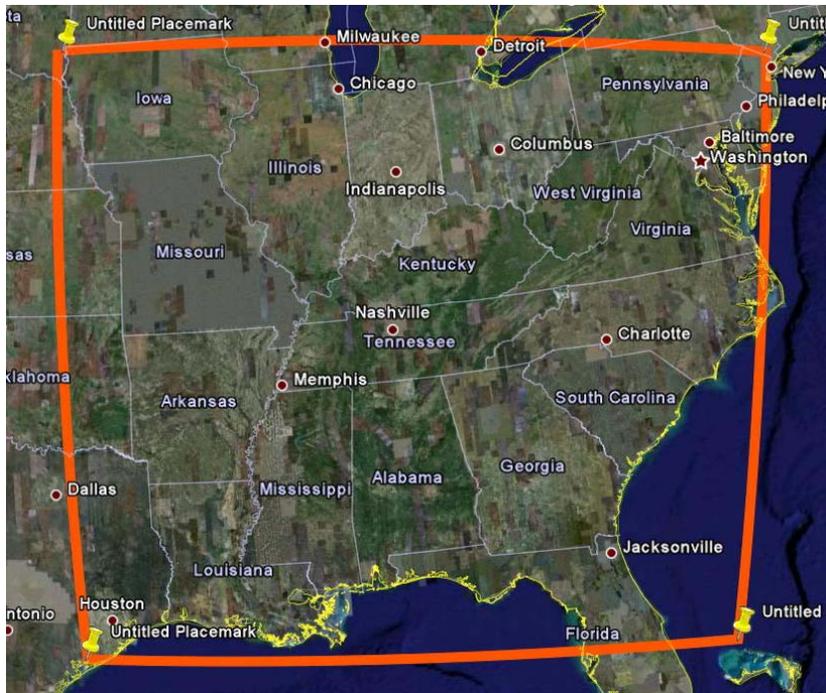


Figure 5-12 A 1000 nm by 1000 nm area

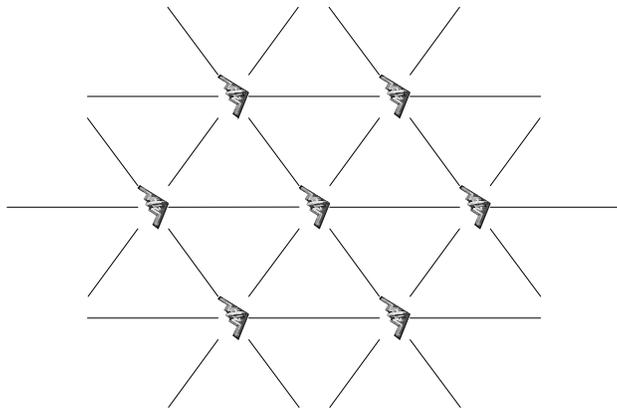


Figure 5-13 A fixed mesh network of 42 mesh points

During the simulation, the regular nodes are randomly deployed in the area. In order to model the real traffic load, a random communication pattern is introduced in the simulation. First, the simulation time is split up into 10 second slots. At each time slot, any pair of regular nodes has a probability of 20% to have UDP communications. As we can expect, the entire traffic load would increase with the increase of regular nodes in the network and eventually consume all the bandwidth. After that, the communication

condition is getting worse if the number of nodes keeps increasing. And it would be very difficult to send out a packet. The throughput between node 0 and node 1, reported as the blue curve in Figure 5-14, is our performance measurement.

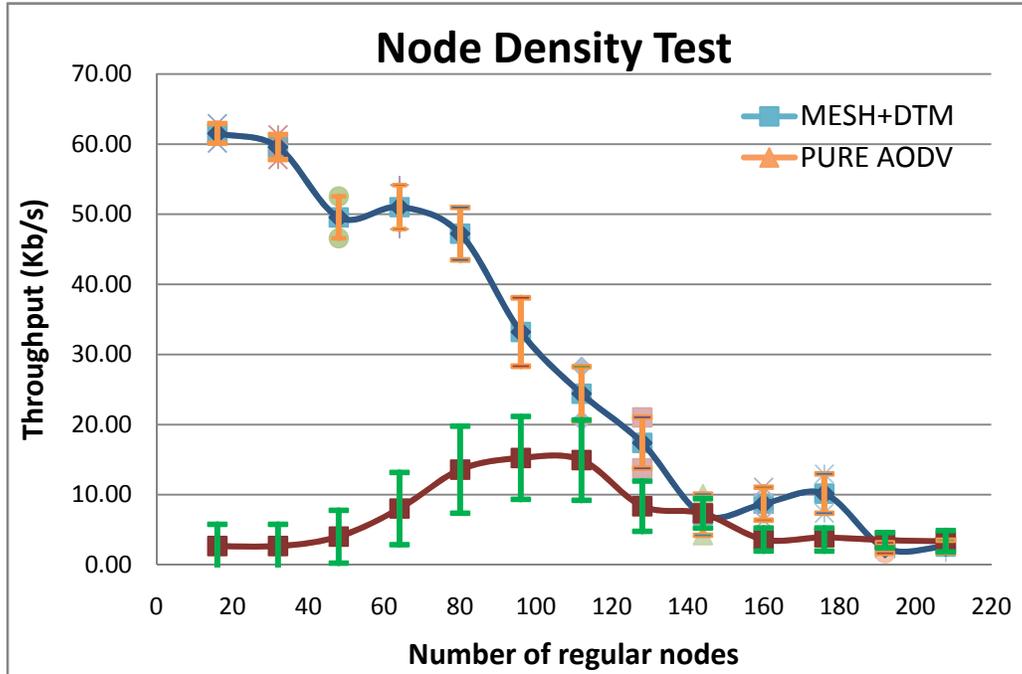


Figure 5-14 Throughput of node density test

We also test the network without mesh and DTM, shown as the red curve in Figure 5-14. At this time, the simulation uses the same random distribution of regular nodes above, but removes the mesh points and DTM. The result shows that traditional AODV has very low throughput when the number of nodes is less than 60, and reaches its maximum throughput around 100 nodes in the network. Since the radio range is 100 nm, less than 60 nodes are not enough to cover the area and form a stable ad hoc route from sender to receiver. As the number of nodes increases to about 100, the random distributed nodes would be possible to cover the 1000 nm × 1000 nm area. After that, the throughput of conventional AODV decreases with the increasing number of nodes, because more traffic is introduced into the network to share the limited bandwidth.

The result in Figure 5-14 demonstrates that our mesh structure and DTM help AODV to form a stable ad hoc route. The proposed solution achieves stable packet delivery and higher throughput than conventional AODV, although the throughput decreases with the

increase of traffic load. We also calculate the 90% confidence intervals for each point on the mesh curve, which are plotted as the vertical bars in Figure 5-14.

5.4 Mesh density analysis

How to efficiently deploy the mesh points is a topic of importance in airborne networks. In this section, we examine the relationship between mesh density and network performance. The mesh density can be measured by the number of mesh points in a fixed area. The simulation still uses an area of $1000 \text{ nm} \times 1000 \text{ nm}$ as before. And the radio ranges are the same as in the previous section. The number of replications for each simulation is still 100. The major difference is that the number of regular nodes is fixed in this simulation, but the mesh density is dynamic. 50 regular nodes are randomly distributed in the area beforehand. Then, a different number of mesh points are further uniformly deployed in the network.

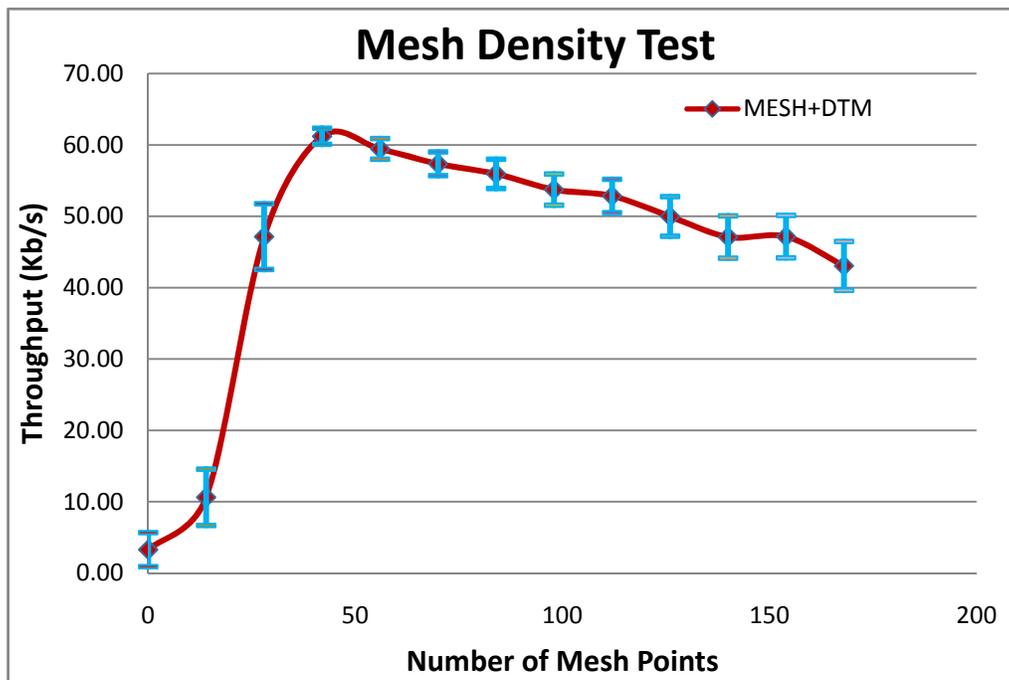


Figure 5-15 Throughput of mesh density test

The result in Figure 5-15 shows that the average throughput is only less than 5 Kbit/s when there is no mesh point in the network. The reason is that 50 nodes cannot cover the $1000 \text{ nm} \times 1000 \text{ nm}$ field, and it stands a good chance that there is no route available

between sender and receiver. As increasing the number of mesh points, the throughput keeps rising and hit its peak around 45. Actually, if the mesh points are uniformly distributed as in Figure 5-15, 42 is the minimum number of mesh points to fully cover the simulation area. After that, the more mesh points in the area, the more overhead there will be. As a result, the throughput decreases with the increase in the number of mesh points. Therefore, the optimized mesh deployment in the area is to form a structure that provides full coverage with as small mesh density as possible. The 90% confidence intervals are also calculated for each point on the curve, which are plotted as the vertical bars in Figure 5-15.

5.5 Summary

In this chapter, our proposed solution is implemented by developing mesh and DTM models for the ns-2 network simulator. The simulation results show that our mesh structure establishes relatively stable links and improve the performance of airborne networks. The node density test illustrates that our mesh structure achieves better performance than conventional AODV. The mesh density simulation demonstrates the relationship between mesh density and network performance. Few mesh points are not enough to cover the simulation area and provide stable links for the area, while redundant mesh points would introduce excessive overhead. An efficient way to deploy the mesh points in the airborne networks is to use as few mesh points as possible to fully cover the area.

Chapter 6. Conclusions

This thesis presents a cluster-based reactive routing protocol for airborne networks. In contrast to conventional ad hoc routing protocols, our solution focuses on improving the routing robustness, handling rapid topology changes and tolerating intermittent links.

To meet these objectives, we form a mesh network with a hierarchical routing structure and introduce a simple self-organizing clustering rule. This clustering rule does not require the cluster head to maintain information regarding cluster membership. As a result, cluster control overhead is kept to a minimum.

We can also utilize location information and DTN techniques to mitigate the influence of intermittent links and drastic topology changes. The DTM can utilize the location information provided by each node, take advantage of the mesh structure, and intelligently maintain a buffer of packets that cannot be immediately delivered. If a temporary link failure occurs in an intermediate router during delivery, the packet, instead of being discarded, is then buffered in that router up to a maximum time-to-live. The DTM also keeps track of link changes and tries to deliver the message as soon as a new path toward the destination is found. If the buffered messages are about to time out and the destination is still unreachable, the DTM will try to deliver the packet to a neighbor closer to the destination when location information is available. Otherwise, it will also try to forward the packet to a neighbor in another cluster and utilize the stable links among mesh points.

The simulation results in section 5.2 show that mesh structure and DTM can be helpful in such networks. The TCP throughput increases 25% when the intermittent rate is 0.5%, and doubles at 15% intermittent rate, as compared to a scenario using the same routing protocol without mesh points or delay tolerant mechanisms. Similar trends are observed with UDP transmission.

The relationship between node density and network performance improvement is also investigated in this thesis. When the node density is low, the regular nodes are sparsely deployed in the area. In such a case, our mesh structure helps to establish stable links for

the airborne network, and greatly improves performance, as shown in Figure 5-14. Even when the node density is large enough to build up a traditional ad hoc network, the additional mesh and DTM techniques still result in improved performance.

The mesh density simulation presented in this thesis informs us on how to efficiently deploy the mesh points in the airborne networks. The more mesh points that are deployed in the area, the more stable links there will be. On the other hand, the more overhead will be introduced into network. Mesh deployment must seek to optimize the trade-off between these two factors.

The main contribution of this research is to propose an effective and efficient routing protocol for airborne networks. The proposed design takes advantage of mesh routers and forms a hierarchical routing structure. A disruption tolerant mechanism is then deployed in the routing protocol to increase the resilience to temporary link or node failure. The research demonstrates our solution effectively adapts to high mobility, dynamic topology and different routing capabilities.

In this project, we have examined the effectiveness of mesh structure and DTM in airborne networks. A tailored DTM algorithm for airborne networks is a topic for future work. Both airborne properties and algorithm complexity need to be considered. A complex algorithm may increase power consumption and computation delay. Another area to be explored in the future is investigating the end-to-end delay, jitter, and packet loss rate. The end-to-end delay reveals the time taken for a packet to be transmitted across a network from source to destination, which is an important metric for real-time traffic. Packet loss rate, from another point of view, demonstrates the channel quality and network performance. The air-to-air scenario is investigated in this thesis. How the mesh structure performs in air-to-ground is another important topic, where slow-moving and energy-constrained nodes should be taken into consideration. The TCP and UDP transmission were examined separately in this thesis. In the future, a mixed network that simultaneously contains both TCP and UDP traffic should be investigated. Meanwhile, how to provide appropriate quality of service (QoS) and security are also interested topics for the future work.

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