PERFORMANCE ANALYSIS AND COMPARISON OF MULTIPLE ROUTING PROTOCOLS IN A LARGE-AREA, HIGH-SPEED MOBILE NODE AD HOC NETWORK

THESIS

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AFIT/GE/ENG/07-28

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THESIS

Presented to the Faculty

Department of Electrical and Computer Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Electrical Engineering

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June 2007

AFIT/GE/ENG/07-28

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AFIT/GE/ENG/07-28

Abstract

The U.S. Air Force is interested in developing a standard ad hoc framework using "heavy" aircraft to route data across large regions. The Zone Routing Protocol (ZRP) has the potential to provide seamless large-scale routing for DoD under the Joint Tactical Radio System (JTRS) program. The goal of this study is to determine if there is a difference between routing protocol performance when operating in a large-area MANET with high-speed mobile nodes. This study analyzes MANET performance when using reactive, proactive, and hybrid routing protocols, specifically AODV, DYMO, Fisheye, and ZRP. This analysis compares the performance of the four routing protocols under the same MANET conditions. Average end-to-end delay, number of packets received, and throughput are the performance metrics used.

Results indicate that routing protocol selection impacts MANET performance. Reactive protocol performance is better than hybrid and proactive protocol performance in each metric. Average ETE delays are lower using AODV (1.17 secs) and DYMO (2.14 secs) than ZRP (201.9 secs) or Fisheye (169.7 secs). Number of packets received is higher using AODV (531.6) and DYMO (670.2) than ZRP (267.3) or Fisheye (186.3). Throughput is higher using AODV (66,500 bps) and DYMO (87,577 bps) than ZRP (33,659) or Fisheye (23,630). The benefits of ZRP and Fisheye are not able to be taken advantage of in the MANET configurations modeled in this research using a "heavy" aircraft ad hoc framework.

Acknowledgments

First and most importantly, I would like to thank my Heavenly Father, who helped me endure and make it through this extremely challenging yet very rewarding research effort.

My deepest thanks go out to my family members, whose encouragement and support kept me grounded and focused upon my end goal. I appreciate their wisdom and humor provided from their own post-grad experiences to bring reality and laughter back into the picture.

I would like to acknowledge my friends and colleagues who have endured their own research endeavors while providing support and encouragement along the way. Specifically, I would like to mention Capt Jason Macdonald who was a friend and a source of help during the entire process.

I would like to express my appreciation to my thesis advisor, Dr. Barry Mullins, for his support and guidance throughout the entirety of this research effort. I appreciate the scholarly wisdom and patience you displayed as I struggled through my research effort.

Lastly, I would like to thank the Air Force Communications Agency and the Air Force Institute of Technology for making this research opportunity possible.

Daniel K. Roberts

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PERFORMANCE ANALYSIS AND COMPARISON OF MULTIPLE ROUTING PROTOCOLS IN A LARGE-AREA, HIGH-SPEED MOBILE NODE AD HOC NETWORK

I. Introduction

In today's world, data communication spans the globe. This is made possible by continuing advances in communication and network technology. Among these advances is the growing study and application of wireless technologies. As wireless data communication becomes more and more prevalent in modern society, the study and development of mobile ad hoc networks has become a major focus of research. Routing the data communications through the ad hoc network is a small, but very important, aspect of network communications. Routing algorithms to perform this function have been developed and studied, but as network technologies evolve and improve, so must routing of the data.

Understanding the importance and prevalence of mobile ad hoc networks and the challenges they face can be applied to the study of battlefield communications. Battlefields frequently exist in regions where advanced technological infrastructure do not exist. Given this dilemma, battlefield communications require portable infrastructure or mobile ad hoc networks to function smoothly and quickly. Because battlefields are unique environments, commercial technologies may not always be suitable for battlefield operations. As in the case of data communications, battlefield environments must deal with unique constraints that are not typical in modern society. Data communication routing in these unique environments must be efficient and timely. Continued research into these battlefield communication challenges should be pursued.

1.1 Motivation

The United States Department of Defense is emphasizing the need for combined and integrated radio development [She00]. This seamless integration of service capabilities for joint missions is a requirement of Joint Vision 2020 [JTR03]. The Air Force Communications Agency builds upon this requirement in its current research on development of a standard framework for an ad hoc airborne network. The goal behind this research is to develop a framework to allow "heavy" aircraft to support ad hoc networking, including support for "daisy chained" repeaters in the air. Development of this framework involves research into multiple layers of the OSI protocol stack.

Routing within the Network Layer is a challenge in the development of this ad hoc framework. With the development of the Joint Tactical Radio System to provide seamless communication integration, the Zone Routing Protocol has been proposed as a potential routing protocol to meet this need [She00][SIT00]. While there are numerous wireless routing algorithms currently available and being developed, discovering a unique routing protocol which best meets DoD requirements of seamless integration requires study.

1.2 Overview and Goals

The physical constraints identified by the Air Force Communications Agency's development of framework for an ad hoc airborne network define the network configurations used in this study. Modeling a network which covers a large region with a small number of high speed "heavy" aircraft with large separation distances creates unique challenges. Using this configuration as the basis for battlefield data communications requires effective routing of those communications. This study observes and compares the performance behavior of the Zone Routing Protocol along with current reactive and proactive routing protocols.

The primary goal of this study is to compare the performance of several routing protocols within the physical constraints identified by the Air Force Communications Agency objectives. The routing protocols chosen are selected to observe the behaviors of reactive, proactive, and hybrid routing. The results generated by this study are meant to assist the Air Force Communications Agency in their further development of a standard framework for an ad hoc airborne network.

1.3 Thesis Layout

This chapter introduces the research focus and provides background motivation for the study. Chapter 2 provides a background review of mobile ad hoc network routing and the routing protocols tested in this research. Chapter 3 presents the testing methodology used to perform the experiments. Chapter 4 presents the results collected during the experiments. A discussion of the simulation statistics, comparison of routing protocols, and analysis of the results are presented. Chapter 5 offers conclusions about the results, identifies areas for further research, and concludes the document.

II. Literature Review

2.1 Introduction

This chapter presents the fundamentals of mobile ad hoc networking, the challenges faced in mobile ad hoc network (MANET) routing, and several routing protocols developed to meet the demands of MANET routing. This research focuses on four specific MANET routing protocols, the Ad Hoc On-Demand Distance Vector (AODV) routing protocol [PeR97], the Dynamic MANET On-demand (DYMO) routing protocol [ChP07], the Fisheye State Routing (FSR) protocol [PGC00a][PGC00b], and the Zone Routing Protocol (ZRP) [HPS02][Bei02]. Section 2.2 presents the background for MANETs and MANET routing. Sections 2.3, 2.4, 2.5, and 2.6 provide details on AODV, DYMO, FSR, and ZRP, respectively. Section 2.7 discusses the Department of Defense (DoD) MANET routing issues and provides an introduction to hybrid routing protocols. The QualNet network modeling tool is the simulation software for this study and is the focus of Section 2.8. Section 2.9 presents current research being performed on the DYMO, FSR and ZRP routing protocols.

2.2 Mobile Ad Hoc Networks (MANET)

2.2.1 MANET Characteristics

In a MANET, communication between nodes does not use an existing infrastructure. Instead, mobile nodes communicate directly with each other without the assistance of fixed devices. For a node to communicate with another node outside of its transmission range, each node within the MANET must be able to act as a router and forward traffic as necessary. A MANET's lack of infrastructure makes it suitable for rapid deployments in global locations without available infrastructure.

By their very nature, MANETs must overcome unique challenges. Due to the mobility of the nodes, a MANET typically consists of nodes that are portable devices with limited transmission power and operates in a dynamically changing topology. MANETs typically span a large area and include a large number of nodes. The limited transmission power creates further challenges by limiting the number of neighbors an individual node can reach. Given this dynamically changing environment, links can become unreliable. Additionally, MANETs typically have to deal with asymmetric links and low bandwidth links between nodes. These unique characteristics of MANETs make routing within this type of network a challenge. [Bei02][RoT99][HaP98][HDL02]

2.2.2 MANET Routing Protocols

MANET research has led to the development of numerous routing algorithms and protocols [Lan03]. Routing protocols perform with differing results, given the various operating conditions of a MANET. Protocol A may be superior to protocol B in a given environment, and protocol B may outperform protocol A in a different environment. Therefore, it is difficult to say one protocol is superior to the other without knowing the network's application.

Routing protocols can be classified as either proactive, reactive, or a hybrid of the two. Each type of network has its strengths and weaknesses, and determination to use one type or the other in a given network depends upon the various conditions and scenarios of that network.

2.2.2.1 Proactive Routing

Proactive routing protocols are table-driven protocols. These protocols attempt to maintain correct routing information of the entire network at all times. Because the network routing tables are constantly maintained, routing for a packet is known without additional setup delay. The weakness of this routing scheme is that a large portion of bandwidth is used to keep the routing information up-to-date. In the case of fast node mobility, route updates may be more frequent than route requests, thus wasting bandwidth because much of the routing information will never be used. [Bei02][PeH99][HaP98]

Proactive routing can further be classified by how often the tables are updated. Updates can be either event driven or scheduled at regular intervals. Event driven updates only occur when changes are detected. The changes are then reported throughout the network. With regular scheduled interval updates, routing information is sent throughout the network at regular intervals. [Lan03]

2.2.2.2 Reactive Routing

Reactive routing protocols are on-demand protocols. These protocols do not attempt to maintain correct routing information on all nodes at all times. Routing information is collected only when it is needed, and route determination depends on sending route queries throughout the network. The primary advantage of reactive routing is that the wireless channel is not subject to the routing overhead data for routes that may never be used. While reactive protocols do not have the fixed overhead required by maintaining continuous routing tables, they may have considerable route discovery delay.

Reactive search procedures can also add a significant amount of control traffic to the network due to query flooding. Because of these weaknesses, reactive routing is less suitable for real-time traffic or in scenarios with a high volume of traffic between a large number of nodes. [Lan03][Bei02][HaP98]

Routing information is collected in the route discovery process. The minimum information required by a node to send data is the next hop in the route. If this next hop information is unavailable, broadcasting is performed. In this procedure, the originating node sends a broadcast message requesting the desired route. Nodes that have routing information will respond to the broadcast. The originating node then chooses a route from the responses. In the case the route is not initially known and needs to be determined, there is an initial setup delay. Many reactive protocols limit this delay through the use of a route cache for established routes. In the case of mobile environments, when routes become invalid over time, the information in the cache times out and is removed. [Lan03]

2.2.2.3 Hybrid Routing

Hybrid routing protocols are a combination of both proactive and reactive routing. They attempt to take advantage of the strengths of purely proactive and reactive routing, while minimizing the weaknesses of both forms of routing. Because of the routing protocol challenges within MANETs mentioned earlier, purely proactive and reactive routing are inefficient [Bei02]. Hybrid routing provides a way to minimize the inefficiencies of MANET routing.

2.3 Ad Hoc On-Demand Distance Vector (AODV) Routing Protocol

AODV is a well-known MANET routing protocol. It was developed by Charles Perkins and Elizabeth Belding-Royer and is one of the most studied and most advanced routing protocols [Lan03][PeR97]. AODV is a reactive routing algorithm that requests a route only when needed and maintains only active communication routes.

2.3.1 Route Discovery

Figure 1 shows an example of the route discovery process. When a node needs to send data to a destination and does not know the route, a route request packet, RREQ, is broadcast. This RREQ propagates throughout the network until the destination is discovered. When the destination is found, a route reply message is returned to the source with the routing information.

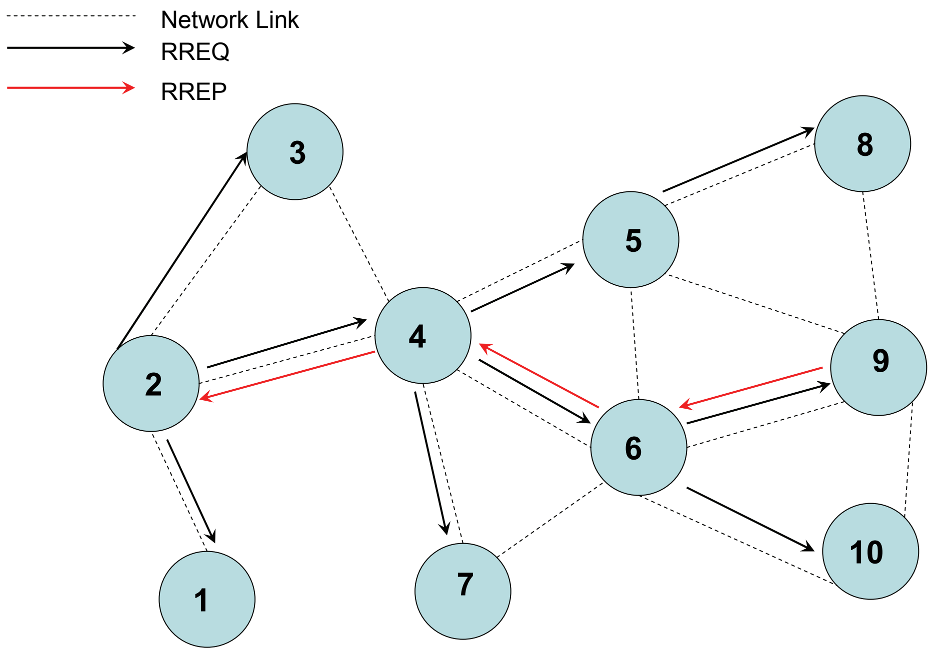

Figure 1. AODV route discovery [Tho07]

Figure shows the process of how the path is determined from the source node, 2, to the destination node, 9. Node 2 propagates a route request packet to its neighbors, nodes 1, 3, and 4. These nodes, in turn, propagate the route request to their neighbors while collecting route data. The route request, along with the path to the source node, is eventually received by the destination node, node 9. Because route data has been collected during the route discovery process, the destination node is able to send its reply message back along the shortest route, as shown by the RREP route. To prevent excess broadcasting of the RREQ, the source node optimizes its search by using an expanding ring search. In this search process, increasingly larger neighborhoods are included to find the destination. A time-to-live field (TTL) in the IP header of the RREQ packet controls the search. [BoK01][Tho07]

2.3.2 Route Maintenance

Routing table entries include a destination, the next hop towards that destination, and a sequence number. Routes are only updated if the sequence number of the incoming message is larger than the existing number. [Lan03]

Routing table entries maintain a route expiration time. Each time that route is used to forward a data packet, the expiration time is updated to the current time plus ACTIVE_ROUTE_TIMEOUT. If the time expires, the routing table entry is no longer valid. [BoK01]

When a broken link occurs or a node receives a packet which it has no forwarding route for, a Route Error (RERR) message is created. The RERR message holds a list of all of the unreachable nodes. Figure 2 depicts a broken link and the generation and flow of a RERR message. The link between node 6 and node 9 has broken. Node 6 creates a RERR message and propagates it back to node 2. The source node can either try to find a new route by initiating a new route discovery for the destination, or the intermediate node may try to repair the route locally. [Tho07]

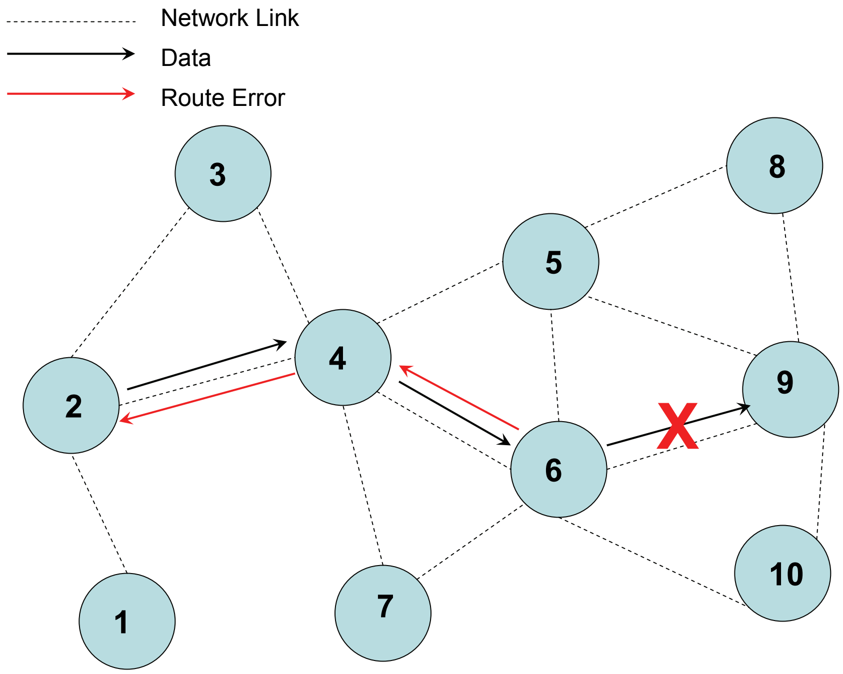

Figure 2. AODV route maintenance [Tho07]

2.3.3 AODV Positives and Negatives

AODV is a good selection for routing when the network is dynamically changing. When nodes are constantly moving and routes are changing at a frequent pace, AODV will perform well. Because of its route discovery mechanism, AODV performs a thorough search of the network to find the destination.

However, as the search expands, AODV will have performance problems. Increased route discovery delays must be taken into account when weighing the benefits and consequences of routing decisions. This route discovery delay will increase in proportion to the number of nodes in the network as the route requests are propagated throughout the network. As the search expands and more nodes broadcast the route request, more bandwidth will be consumed due to the increased route request propagation.

2.4 Dynamic MANET On-Demand (DYMO) Routing Protocol

2.4.1 DYMO Background

DYMO is a recently proposed on-demand routing protocol. It is currently being considered by the Internet Engineering Task Force (IETF) MANET working group (WG) to be the single IETF reactive routing protocol. This process began in 2005 with the rechartering of the MANET WG [IMC07] "to develop a single reactive and single proactive routing protocol" [ChM05]. The focus of this new charter is to standardize IP routing protocols for use in dynamic multihop wireless networks using the best practices to date. The routing protocols being considered, of which DYMO represents the reactive protocol, are expected to combine the best features from the four current experimental MANET protocols: AODV, Dynamic Source Routing (DSR), Optimized Link State Routing (OLSR), and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF). [ChM05][Tho07]

DYMO is a successor to AODV. It is a simplified combination of the AODV and DSR routing protocols. It operates similarly to AODV and maintains the basic functionality of route discovery and route maintenance, but does so without added features or extensions. DYMO achieves its goal through simplification. [ChM05][Tho07]

DYMO uses AODV as a basis for its operations, combining the concepts of AODV with Path Accumulation (AODV-PA) and AODVjr. The sole modification of AODV-PA is to add the source route path accumulation feature of DSR to AODV [GBP03]. In DSR this operates such that every node that forwards an RREQ or an RREP adds its own address to the data packet. This is the way that nodes learn the routes to other nodes. AODVjr modifies AODV such that only the essential elements of AODV are kept [ChK02]. Sequence numbers, hop count, Hello messages, RERR messages, gratuitous RREPs, and precursor lists are not included in AODVjr. The basic functionality of route discovery using RREQ and RREP is all that remains, where only the destination responds to RREQs. DYMO uses the path accumulation functionality from AODV-PA and DSR. Compared to AODVjr, DYMO keeps sequence numbers, hop count, and RERR messages. [Tho07]

2.4.2 DYMO Operations

DYMO performs route discovery and route maintenance. Route discovery is performed on-demand when a node sends packet to a destination not in its routing table. Broadcasting is used to flood the network with the route request. If the destination is discovered, a reply message containing the discovered path is sent back. A routing table with information about nodes is maintained by each node.

2.4.2.1 Route Discovery

Figure 3 illustrates the route discovery process. In the figure, node 2, the source, wants to communicate with node 9, the destination. To begin this communication process, node 2 generates a RREQ message which includes its own address, its sequence number, a hop count for the originating node set to an initial value of 1, and the target address. This RREQ message is broadcast throughout the network. This broadcasting is controlled in such a manner that a node will only forward the RREQ if it has not done so previously. Sequence numbers provide this information. Each additional node that forwards the RREQ can add its address and sequence number to the RREQ. This is shown in the figure, as nodes 4 and 6 add information to the RREQ they broadcast. Once the source node sends the RREQ, it then waits to receive a RREP message from the destination. If the RREP is not received within a specified waiting time, the RREQ may be resent. This waiting time can be set according to the network configuration.

Once an RREQ is received by a node, that node can create reverse routes to the nodes which have forwarded the RREQ by using the addresses the RREQ has accumulated. This is how the RREP is sent back to the source node. Node 9 receives the RREQ and is able to build a reverse route using the accumulated address information collected by the RREQ. This route is then used to send the RREP back to node 2. [Tho07]

2.4.2.2 Route Maintenance

Route maintenance is necessary to respond to changes that take place within the MANET due to the dynamic nature of the network. Nodes must continuously monitor the active links and maintain up-to-date routing information within their tables. A route error (RERR) message must be sent by a node if it receives a packet with a destination for which it does not have an active route. [Tho07]

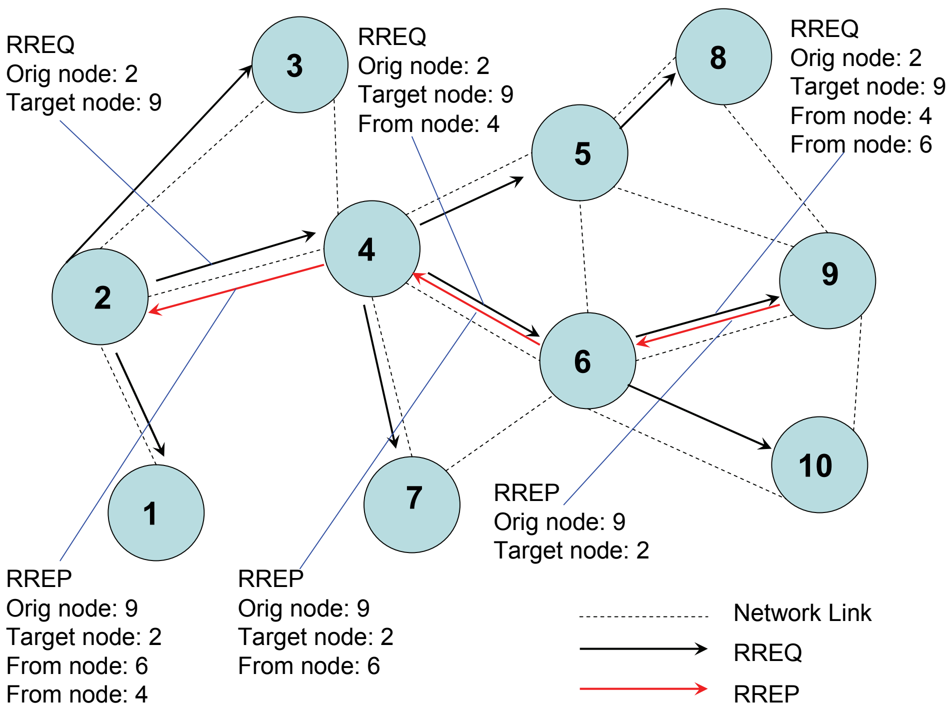

Figure 3. DYMO Route Discovery [Tho07]

The RERR process is depicted in Figure 4. In this example, node 6 has received a packet that needs to go to node 9, but the link between nodes 6 and 9 is broken. Because of this broken link, node 6 creates an RERR message and propagates this message towards the source node, node 2. Nodes which receive the RERR message update their routing tables with the new information. [Tho07]

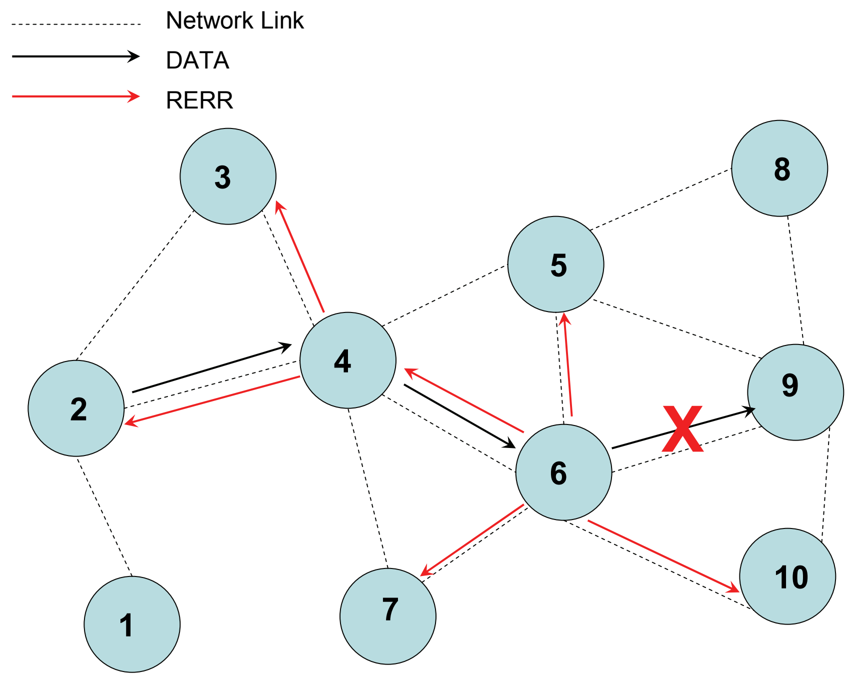

Figure 4. DYMO RERR process [Tho07]

2.4.3 DYMO Positives and Negatives

Because of DYMO's similarities to AODV, it can be expected to perform in a similar fashion. DYMO is also a good selection for routing when the network is dynamically changing. When nodes are constantly moving and routes are changing at a frequent pace, DYMO can be expected to perform well. Because of its similar route discovery mechanism to AODV, DYMO also performs a thorough search of the network to find the destination.

However, DYMO will run into the same problems as AODV as the number of nodes increase. DYMO may experience more difficulty with larger networks because it is a simplified version of AODV. Without the added features or extensions of AODV, when AODV performance is poor, DYMO performance may be worse. As with AODV, increased route discovery delays must be taken into account when weighing the benefits and consequences of routing decisions. This route discovery delay will increase in proportion to the number of nodes in the network as the route requests are propagated throughout the network. As the network becomes larger and more nodes broadcast the route request, more bandwidth will be consumed due to the increased route request propagation.

2.5 Fisheye State Routing (FSR) Protocol

FSR is a proactive routing protocol that uses a hierarchical, or layered, routing scheme. The "fisheye" technique was developed to reduce the size of the information needed for data representation. This routing scheme is representative of how the eye of a fish operates. Near the focal point, the eye of the fish is able to capture very high detail, but as the distance from the focal point increases, the detail captured by the eye decreases. In fisheye routing, this technique is applied to distance and path information. Near the focal point, accurate distance and path quality information is maintained in higher detail. As distance from the focal point increases, less routing detail is maintained. [PGC00a][PGC00b][GHP02]

2.5.1 FSR Characteristics

In FSR, each node maintains a topology map which is a link state table based upon up-to-date information received from its neighbors. To reduce overhead traffic, nodes update their routing information by exchanging topology maps periodically with local neighbors, rather than performing event-driven updates or network flooding. During this exchange process, table entries are updated based upon sequence number – an entry with a larger sequence number replaces those with smaller numbers. [PGC00a][PGC00b][GHP02]

2.5.2 Applying the "Fisheye" Technique

Figure 5 illustrates how the fisheye technique is applied to a MANET. When the size of a network increases, sending update messages may potentially consume the bandwidth. FSR uses the fisheye technique to reduce the size of the update message without affecting routing. In the figure, three fisheye scopes are defined with respect to the focal point, node 11. Each scope is defined by the set of nodes that can be reached by a certain number of hops. The figure illustrates three scopes of size 1, 2, and greater than 2 hops. Selection of scope levels and radius are dependent upon individual network requirements. [PGC00a][PGC00b][GHP02]

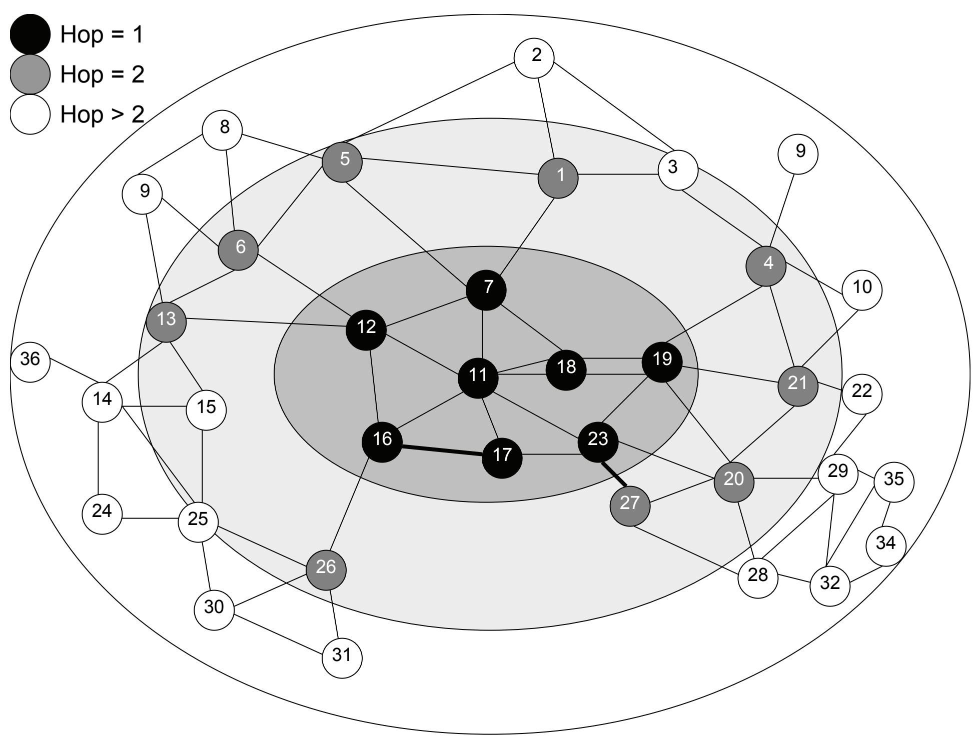

Figure 5. Fisheye scope [PGC00a]

Routing overhead is reduced by modifying how often entries are propagated from the central node. Nodes within the smaller scope receive updates more frequently than those in the larger scopes. Because of this frequency modification, overhead can be reduced. However, while neighboring nodes are receiving timely updates, large latencies are created from more distant nodes. Compensating for this latency increase is the fact that as the packets get closer to the central node, the routes are increasingly more accurate. [PGC00a][PGC00b][GHP02]

2.5.3 FSR Positives and Negatives

FSR is more desirable for large-scale MANETs where bandwidth is low and mobility is high [GHP02]. In a small MANET, the benefits of using FSR scopes would not be an advantage because route discovery and route maintenance are simple reactive and proactive tasks. The advantages of using the fisheye techniques become noticeable in larger networks. When bandwidth is low, the bandwidth-saving features of fisheye become important. If the bandwidth is high, fisheye bandwidth consumption will be lower than that of other routing protocols, but no added benefit of FSR will be seen. Networks with high mobility can take advantage of the differing update frequencies between scopes. As nodes are moving in and out of the central node's scope, the more frequent updates of the higher order scopes allow the central node to maintain its local routing table when the mobility is high. As the mobility decreases, the advantage seen in FSR is decreased.

2.6 Zone Routing Protocol (ZRP)

ZRP is a hybrid routing framework which combines the approaches of proactive and reactive routing protocols. ZRP is made up of zones centered about each node. Each node maintains a routing table to destinations within its zone. This allows routes within the zone to be known immediately. For destinations outside of the zone, ZRP uses a reactive approach to specifically query border nodes, which in turn search their zones proactively, returning a route if the destination is found or querying their border nodes in a continuing fashion. This hybrid approach takes advantage of both proactive and reactive routing. The hybrid nature of ZRP makes it "suitable for a wide variety of mobile ad hoc networks, especially those with large network spans and diverse mobility patterns." [Lan03][HPS02][Bei02]

2.6.1 Routing Zones

Since each node has a defined routing zone, neighboring nodes have overlapping zones. ZRP is configured by a single parameter, the routing zone radius [HPS02]. Routing zones are defined by a radius, ρ, which is expressed by a selected number of hops. Zones include all nodes whose distance from the selected node is at most ρ hops from that node. Figure 6 shows an example of the zone radius about node S, with a radius of 2. As seen in the depiction, node K does not belong in the zone of node S because it can only be reached with more than 2 hops. Therefore, zones are not defined by physical distance, but are defined by hops, which are dependent upon the transmission power and receiver sensitivity of each individual node.

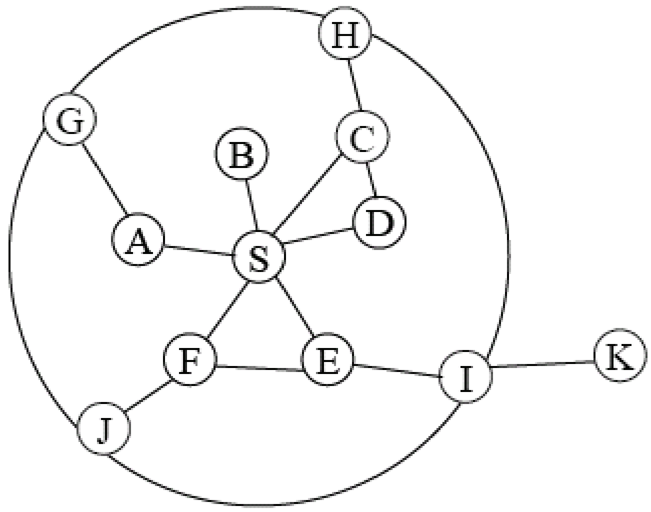

Figure 6. Routing zone of node S with radius of 2 [Bei02]

Nodes within a zone are either peripheral nodes or interior nodes. Peripheral nodes are those nodes whose maximum distance to the central nodes is exactly equal to the zone radius. The interior nodes are those nodes whose maximum distance to the central node is less than the zone radius. [Bei02][HPS02]

Adjusting the transmission power of the nodes regulates the number of nodes in a routing zone. Raising the power increases the number of nodes which are directly reachable, while lowering the power decreases the number of nodes which can be reached. Optimization of ZRP within a network is achieved when the best possible balance can be found. If the zone has a radius of one, then routing is purely reactive. Zones should be large enough to provide sufficient reachability and redundancy. However, as the radius approaches infinity, routing becomes purely proactive while traffic updates congest the network and the probability of local contention increases. Selection of a zone radius becomes a tradeoff between routing efficiency of proactive routing and the increasing traffic for maintaining an updated routing table of the zone. [Bei02][PeH99]

2.6.2 ZRP Routing

ZRP routing is performed using three separate routing components: the proactive routing component, Intrazone Routing Protocol (IARP); the reactive routing component, Interzone Routing Protocol (IERP); and a query delivery service, Bordercast Resolution Protocol (BRP). Figure 7 shows the relationship between these three components and is discussed in more depth further.

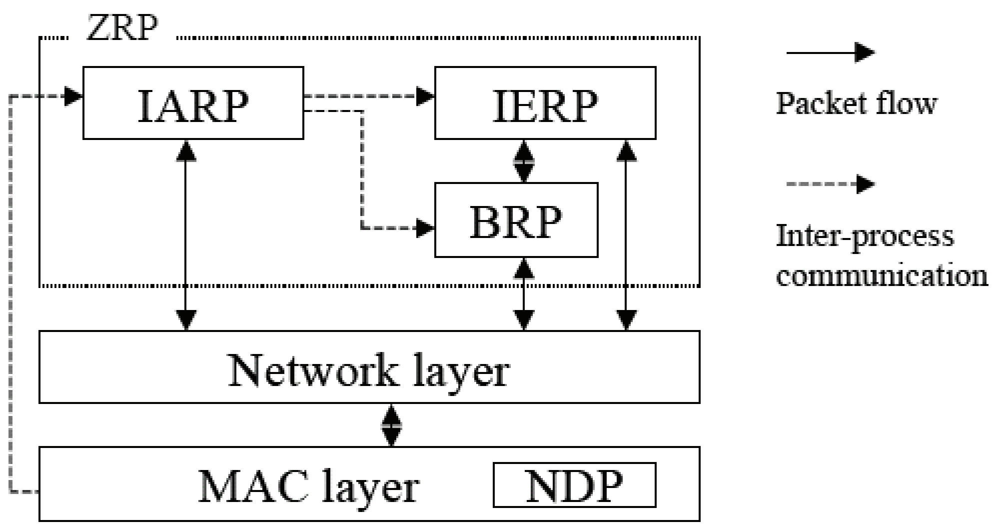

Figure 7. ZRP component architecture [HaP01]

IARP is not a specific routing protocol. It belongs to "a family of limited-depth, proactive link-state routing protocols" which function to maintain routing information for a node's routing zone [Bei02]. An existing proactive routing protocol can be converted to an IARP by 1) limiting link state updates to the scope of the source node's routing zone, and 2) by relying on a separate protocol, the Neighbor Discovery Protocol (NDP), to inform a node of its neighbors. [HPS01c]

IERP is also not a specific routing protocol, but belongs to a family of reactive routing protocols that provide route discovery and route maintenance services. The IERP protocol is dependent upon the local connectivity maintained by the IARP [Bei02]. An existing reactive routing protocol can be converted to an IERP by following several guidelines:

- Local proactive route updates and neighbor advertisements should be disabled because IARP performs this functionality.

- The importation of IARP routes must be supported by its routing table.

- Route lookups into the IARP routing table must be supported.

- The broadcast of route request messages needs to be replaced to use the bordercast service, provided by BRP.

- Redundant query termination messages need to be disabled because this is handled by BRP.

- Route request broadcast jitter needs to be disabled because this is performed by BRP. [HPS01a]

Bordercasting reduces the traffic for global route discovery by taking advantage of the proactive routing maintenance for each zone. Bordercasting uses the topology information of each zone, provided by IARP, to direct query requests specifically to border nodes of the zone. BRP performs this bordercast packet delivery service. [Bei02][HPS02][HPS01b]

2.6.2.1 Neighbor Detection

Looking at Figure 7, ZRP uses Neighbor Detection Protocol (NDP) provided by the Media Access Control (MAC) layer to detect neighbor nodes and link failures. Neighboring nodes receive "HELLO" beacons, which are transmitted by NDP at regular intervals, and update their tables accordingly. After a specified time, if no beacons have been received from a neighbor, that neighbor is removed from the table. If a node's MAC layer does not include NDP, the neighbor discovery functionality needs to be performed by the IARP. [Bei02][HaP98]

NDP triggers route updates and notifies IARP when the neighbor table is updated. IERP responds to queries using the routing table of IARP and forwards the queries with BRP. BRP guides the routing queries away from the query source using the routing table of IARP. [Bei02][HaP01]

2.6.2.2 Routing

When a node wants to send a packet, it checks to see if the destination is inside of its local zone using routing information from IARP. If the destination is found within its local zone, the packet is routed proactively. If the destination is outside of the node's local zone, reactive routing is applied. [Bei02][HPS01b]

Reactive routing, IERP, has two separate phases: the route request phase and the route reply phase. This can be seen in Figure 8. In the route request phase, the source node, labeled S in the figure, uses BRP to send a route request packet to its peripheral nodes. If the receiving node knows the route to the destination, it responds by sending a route reply back to the source node. Otherwise, it bordercasts the route request and the process continues. In this manner, the route request spreads throughout the network. If a node receives multiple copies of the same route request, the node considers them redundant and discards them. In the route reply phase, a reply is sent by any node that knows a route to the destination. For a reply to be sent back to the source node, routing information must be collected as the request is being sent throughout the network. As soon as the destination is discovered to be within a receiving node's zone, the reply is sent following the path that was generated in the route discovery process. [Bei02][HPS01a][HPS01b][HaP01]

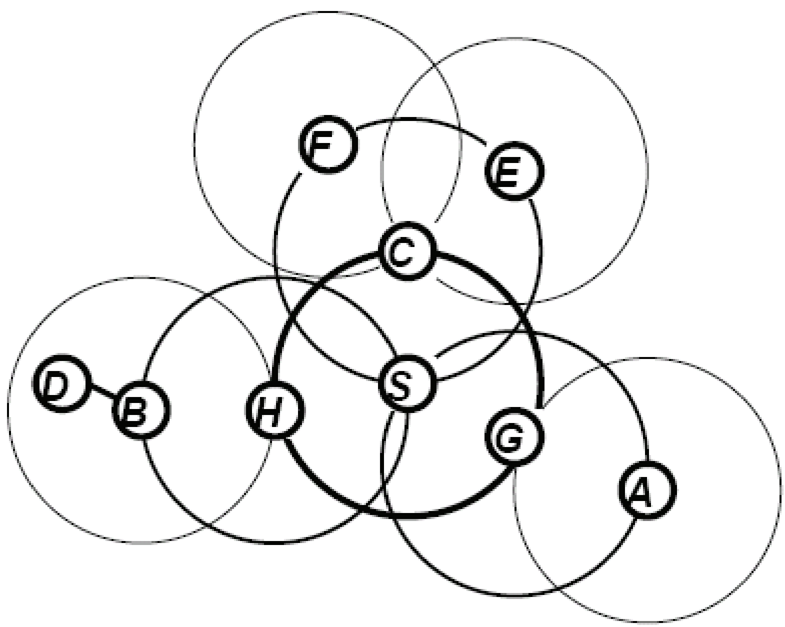

Figure 8. IERP operation [HaP01]

2.6.2.3 Route Maintenance

In ad hoc networks, route maintenance is extremely important because of the dynamic nature of the node mobility. As the nodes travel relative to each other and are capable of only limited radio coverage, links are easily established and broken. If a route contains a broken link, new route discovery or route repair must be performed. Until this new route is available, packets are either delayed or dropped.

ZRP uses the knowledge of local topology to perform route maintenance. The characteristics of the zones make it possible for link failures and sub-optimal routes to be bypassed. [Bei02][HPS01a]

2.6.2.4 Query-control Mechanisms

In the distribution of query requests, bordercasting is more efficient than flooding because route requests are sent only to peripheral nodes instead of every node. However, because each node maintains its own local zone, the routing zones of neighboring nodes overlap. Because of this overlap, every node is potentially a peripheral node for any given zone, thereby potentially generating more traffic than pure flooding. Query-control mechanisms need to be in place to take advantage of the nodal zone coverage created by ZRP. Once a node bordercasts a query, it's zone has been completely covered. [Bei02][HaP01]

ZRP uses several query-control mechanisms to direct queries away from covered zones and terminate redundant route requests. Query detection, early termination, and random-query processing delay are the query-control mechanisms used by ZRP. [Bei02][HaP01]

2.6.3 ZRP Implementation

By limiting the scope of the routing zone to ρ hops, a traditional link-state protocol can be modified to be an IARP. A time-to-live (TTL) field in the link-state update packet implements this limited scope. The field begins with a value of ρ-1 when the packet leaves the source node. When the TTL value reaches zero, the packet is discarded. When each node updates its link state table, sources that are farther than ρ-1 hops away are discarded. [Bei02][HPS01c]

A reactive routing protocol can be converted into an IERP. For a reactive routing protocol to be used as an IERP, it needs to be able to import IARP routes into its routing table and to be able to support lookups with the IARP table. Any local proactive route updates are performed solely by the IARP. Instead of broadcasting route requests, the reactive protocol needs to bordercast the queries with BRP. For this to occur, the reactive protocol's flood control and redundant query termination functions need to be disabled. IARP needs to support the link-state metrics that are consistent with the metrics of IERP. This is required for the IERP to import IARP routes to support route maintenance. [Bei02][HPS01a]

BRP forwards the IERP route requests to the peripheral nodes of the bordercasting node. BRP uses a multicast tree and delivers the query to the IERP at every hop. To keep track of the nodes that have been covered by the query when a request has been received, a node marks off the interior nodes as being covered and reconstructs its bordercast tree and stores this state in cache. The BRP packet contains the following information: the query source and destination address, the query ID, and the previous bordercaster address. BRP transports the route request as an encapsulated packet. To perform its function, BRP uses the routing table and link-state table of the IARP as well as a cache of detected queries from the node, which contains the query source, the query ID, the BRP cache ID, and the previous bordercaster. BRP uses a query coverage map which graphs every combination of query source and query ID. [Bei02][HPS01b]

2.6.4 ZRP Positives and Negatives

ZRP is a good selection for routing over a large-scale network consisting of mobile and stationary nodes, where neither a purely proactive or reactive routing protocol would be a good choice. However, ZRP performance is dependent upon choice of zone radius. If the radius chosen is too small, ZRP becomes completely reactive and the negatives observed in reactive routing appear: increased route discovery times and increased route discovery traffic. However, if the radius selected is too large, ZRP functions more proactively and the negatives observed in proactive routing appear: increased bandwidth consumption as node routing tables are maintained. To minimize these negative impacts, zone radius selection needs to be optimized. ZRP will perform well when the positives of both reactive and proactive routing can be taken advantage of.

ZRP can be expected to perform poorly in completely mobile networks or completely stationary networks. There are routing protocols developed that will outperform ZRP in these types of networks. Also, ZRP benefits can be expected to be lost in networks with a small number of nodes. Given a small network, route discovery times for reactive routing are low and the consumption of bandwidth for table maintenance in proactive routing is low.

2.7 Department of Defense MANET Routing Issues

The 1997 Quadrennial Defense Review (QDR) emphasized the need for all U.S. DoD services to combine and integrate all tactical radio development. Out of this QDR, the Joint Tactical Radio System was created. [She00]

The Mission Needs Statement (MNS) for the Joint Tactical Radio, dated 21 August 1997, outlines the requirements for the JTRS. The idea behind JTRS is to develop a software-programmable and hardware-configurable digital radio system to provide increased interoperability, flexibility, and adaptability for wartime communications [JTR03]. JTRS lays the foundation for allowing the U.S. forces to operate together in a "seamless", near real-time environment via voice, video, and data communications [Fei05]. This seamless integration of service capabilities for Joint missions is a requirement of Joint Vision 2020 [JTR03]. Figure 9 provides a graphical view of the many different DoD assets which create the complexities of routing and forms a basis as to the challenges and necessities for seamless integration of DoD communication [JTR03].

One of the primary objectives of JTRS is to be able to form the radios into a MANET [She00][JTR03]. Because of these seamless integration and MANET requirements, the routing of data becomes an essential piece to this puzzle. Hybrid routing protocols, with their proactive and reactive capabilities, seem best suited for this challenge, with ZRP having been suggested as a potential routing protocol for JTRS [She00][SIT00].

2.8 QualNet 4.0

QualNet 4.0 is a comprehensive network modeling software used to study and observe the performance of various simulated networks. It can be used for applications in wireless, wired, and mixed network platforms. [QPT06]

QualNet was chosen as the simulation tool in this study because the routing protocols AODV, DYMO, FSR, and ZRP, are built into the wireless library. [QUG06]

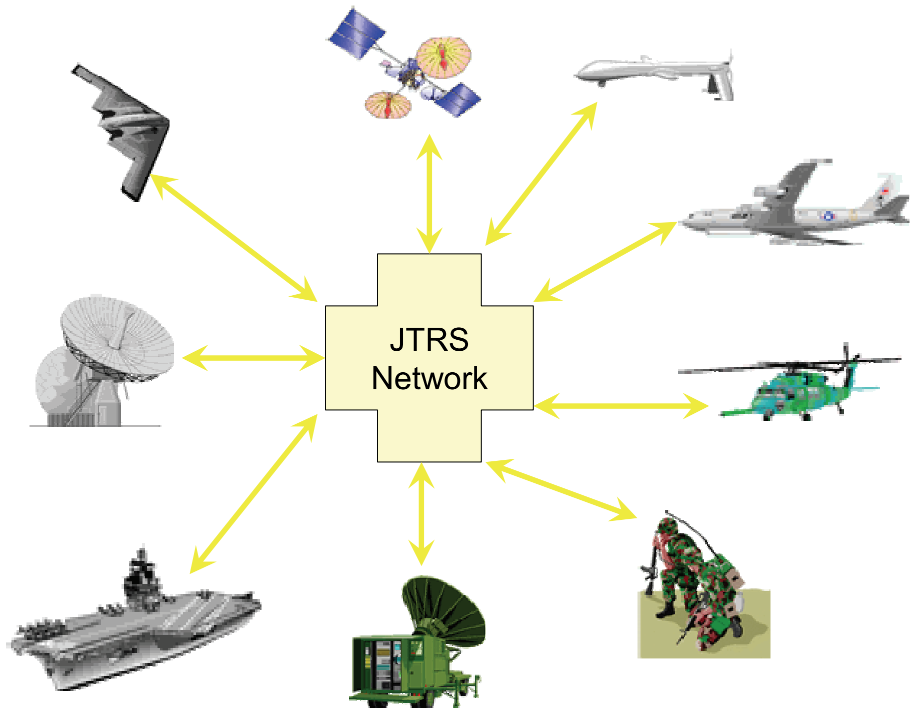

Figure 9. DoD assets integrated through JTRS [JTR03]

2.9 Current Studies with Routing Protocols

The study of routing protocols and algorithms is an on-going field of research. Over the past several years, DYMO, FSR, and ZRP have been developed, simulated and analyzed under differing sets of conditions, while being compared against different routing protocols. Along with this comparison analysis research, attempts to enhance these routing protocols are being studied as well.

2.9.1 Current DYMO Research

Because DYMO is a recently developed routing protocol, it is safe to say that all research that has been done with DYMO is current. As described in [ChM05], the IETF has been tasked to develop a single reactive routing protocol using the best practices from MANET experience. The IETF draft detailing DYMO is currently on version 8 [ChP07]. NIST, OPNET, and Linux implementations of DYMO have been built [Kle07][KuG07] [Tho07]. Preliminary experimentation showed that DYMO throughput performance was similar to AODV throughput [Tho07].

[Zap05] is an IETF draft on the Secure Dynamic MANET On-Demand (SDYMO) Routing Protocol. SDYMO attempts to extend the DYMO routing protocol by providing security features, such as integrity and authentication, to protect the route discovery mechanism.

[KaK07] is an IETF draft on the Quality of Service (QoS) extension to DYMO. Discovering and maintaining QoS routes is the premise behind this extension. This draft identifies the route discovery and route maintenance procedures while using the QoS extension. The route discovery process is the same as DYMO, but the new QRREQ message contains required QoS information needed to select the proper route.

2.9.2 Current FSR and ZRP Research

2.9.2.1 Fisheye Zone Routing Protocol (FZRP)

[YaT05] proposes a new routing protocol called Fisheye Zone Routing Protocol. This new protocol adapts FSR ideas into ZRP, creating a more efficient routing protocol. By adapting the Fisheye idea, FZRP is able to use a multi-level routing zone structure. FZRP offers the advantage of each node maintaining a larger zone while experiencing only a slight increase in overhead traffic.

FZRP identifies two levels of routing zones: the basic zone and the extended zone. This is shown in Figure 10. In the illustration, the basic zone has a 2-hop radius and the extended zone has a 4-hop radius. Different update frequencies are used by the basic and extended zones. The basic zone is updated and maintained at regular intervals, while the extended zone is maintained at a reduced frequency. [YaT05]

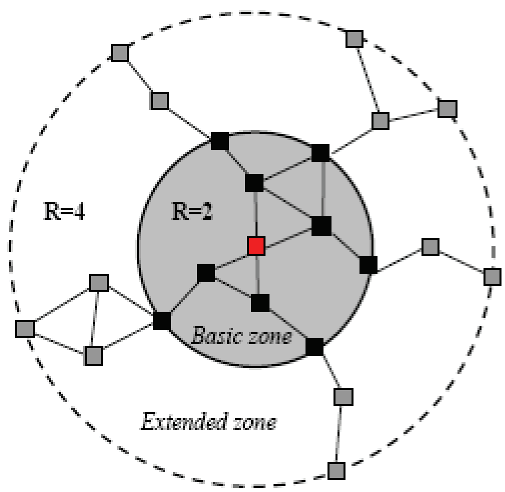

Figure 10. FZRP two-level zone routing [YaT05]

FZRP performance was compared against the performance of ZRP. Maintenance overhead (number of maintenance packets per second), route finding cost (number of route request packets generated per route), and hit ratio of FZRP extended zone were measured and compared. As illustrated in Figure 11, maintenance overhead for FZRP (basic radius of 2, extended radius of 4) was less than that of ZRP (zone radius 2 and 4), and as the pause time is increased for decreased mobility, maintenance overhead for FZRP maintenance overhead approaches that overhead required from ZRP with a radius of 2.

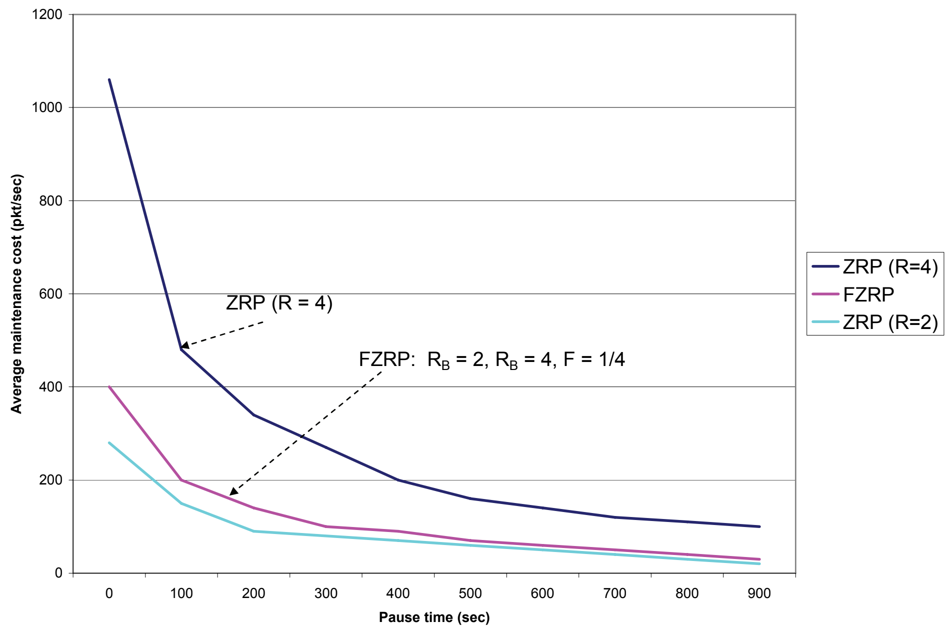

Figure 11. Average maintenance overhead [YaT05]

As shown in Figure 12, the route-finding cost of FZRP is smaller than that of ZRP. These results are observed because bordercasting costs are reduced with FZRP.

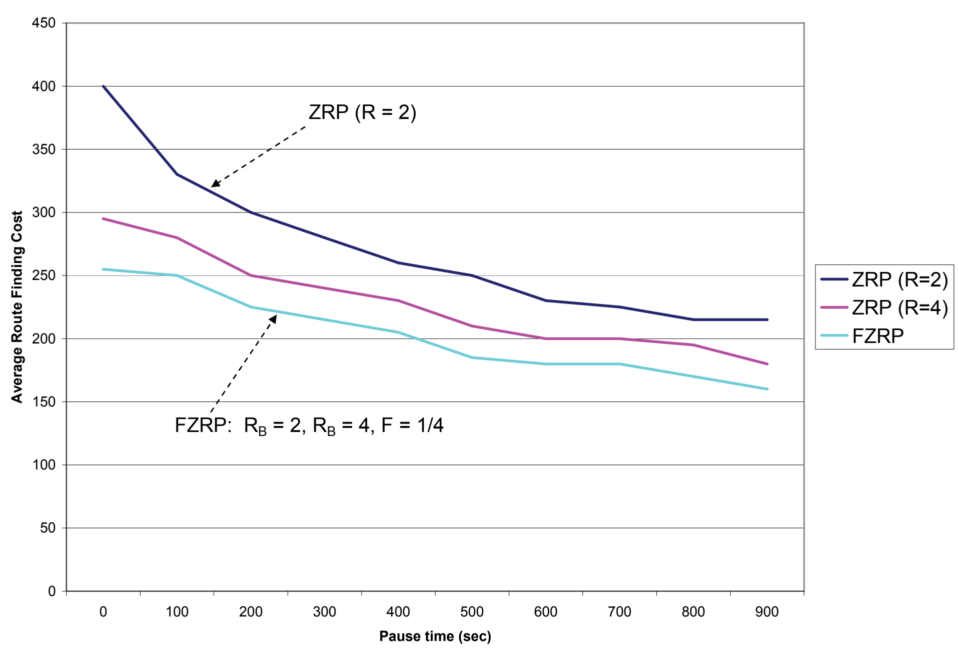

Figure 12. Average route-finding cost [YaT05]

Figure 13 shows the hit ratios (success rates) observed by FZRP and ZRP. While ZRP achieved 100% success rates, FZRP performed remarkably well, achieving success rates over 96%. [YaT05]

[YaT05] concludes that FZRP is more efficient than ZRP in route finding while only observing a slight increase in maintenance overhead.

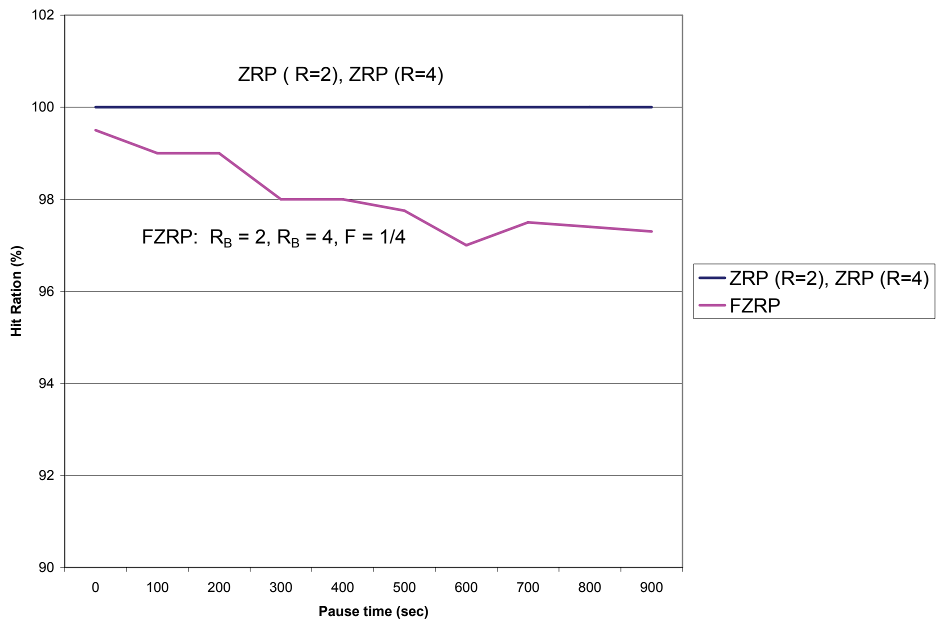

Figure 13. Hit ratios [YaT05]

2.9.2.2 Multicast ZRP (MZRP)

[ZhJ03] modified the ZRP for multicast routing. This proposed new algorithm is called MZRP, and it is shared-tree based. MZRP proactively maintains multicast tree membership information while making on-demand route requests with an efficient query control mechanism. MZRP improves the data packet delivery ratio by using IP tunnel in data transmission. Performance of MZRP was compared against On-Demand Multicast Routing Protocol (ODMRP) to test the tree-based protocol, MZRP, against a mesh-based protocol, ODMRP. The results of this study indicated that both tree-based and mesh-based protocols provide good routing performance in a multicast environment. However, MZRP scales better than ODMRP, resulting in less routing overhead. [ZhJ03]

2.9.2.3 Modified ZRP (M-ZRP)

[VeP05a] extends the reactive part of ZRP to increase the efficiency of service discovery by encapsulating service information within the routing layer messages. Thus, when a node is requesting a service while searching for that service, it is informed of the route to the service provider at the same time it discovers the service. This modified version of ZRP is labeled M-ZRP. This modified approach combines route discovery with service discovery, which allows the simultaneous discovery of both available services and routes thereby reducing message broadcasting and, hence, node power consumption. Results also show that a cross-layer service discovery implementation scheme (piggybacking service information in routing messages) consistently outperforms that of traditional application-layer service discovery scheme, based on flooding limitations in terms of battery consumption. M-ZRP provides less battery consumption (up to 50%) and higher service discovery capability (up to 30%) than ZRP [VeP05a]. M-ZRP has also been called extended ZRP, or E-ZRP [VeP05b].

2.9.2.4 Performance of MANET protocols in Realistic Scenarios

[HBT03] is a comprehensive look on how common MANET routing protocols perform on realistic network scenarios. ZRP was studied, along with AODV, DSR, Optimized Link State Routing (OLSR), and Open Shortest Path First (OSPF). The simulation scenarios used in this study are based upon an actual exercise performed by the DARPA Future Combat Systems Communications Program. Node mobility was generated from exercise GPS log data, and traffic was simulated by using a model of the traffic generation tool from the live exercise. Because of the particular nature of the scenario being tested, it was observed that AODV performed best. The study concluded that ZRP performance could come close to that of AODV by modifying some of the parameters within the limitations of the scenario but did not expand on this conclusion. [HBT03]

2.9.2.5 Performance of MANET protocols in Large-Scale Scenarios

[HBT04] is a comprehensive look on how common MANET routing protocols perform in large-scale networks. ZRP was studied, along with AODV, DSR, and OLSR. Network size experiments looked at the effects caused by adding additional nodes to the network. As shown in Figure 14, ZRP throughput showed a steep decline between 9 and 200 nodes, but leveled off. However, the throughput seen was much less than that of DSR and AODV. Node density experiments looked at the effects caused by increasing node density by using a grid topology with a fixed number of nodes, a fixed number of senders and receivers, and by varying neighbor distance. ZRP and AODV performed similarly, both using fewer control packets in a more sparse network. This result indicates that both of these protocols may have difficulty in a network with a small number of neighbors. Hop count experiments looked at the effects caused by increasing the distance between the sources and their destinations. ZRP performance was indicative of whether the proactive part or the reactive part of the protocol was being used. [HBT04]

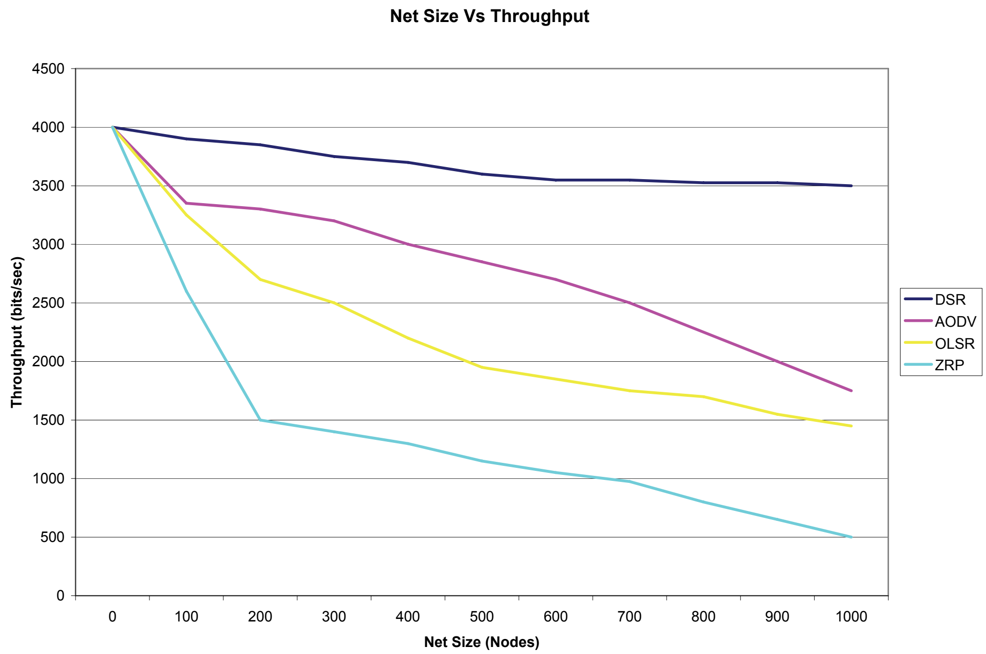

Figure 14. Throughput for Network Size (2 Mbps maximum link capacity) [HBT04]

2.10 Summary

This chapter began with a basic introduction of MANETs and MANET routing. An in-depth discussion of AODV, DYMO, FSR, STAR and ZRP followed. Seamless integration of DoD communications was then identified as a motivator for this study. Following this was a brief introduction to the QualNet network modeler. Finally, recent research efforts with ADV and ZRP were presented.

III. Methodology

This chapter provides the methodology used to investigate the performance of four specific routing protocols in a large-area, high-speed MANET. The necessary information to duplicate this experiment is provided in this chapter.

3.1 Problem Definition

3.1.1 Goals and Hypothesis

The goal of this study is to determine if there is a difference between routing protocols operating over a large area with high-speed mobile nodes in a MANET. This study addresses one primary question of interest: What difference is observed in MANET performance when using a reactive, proactive, or hybrid routing protocol, specifically AODV, DYMO, Fisheye, and ZRP, under the large-area, high-speed mobile node network conditions?

3.1.2 Approach

This study addresses this question by comparing the operation of a MANET using the four routing protocols under the same conditions. Modeling a mobile network over a 500 mile by 500 mile region and running simulations over that network provides data that can be used to gain insight into the performance of the specific routing protocols. Thus, by testing the proactive, reactive, and hybrid protocols under the same conditions, differences can be observed and comparisons made between the four protocols.

This experiment simulates an environment where high-speed mobile nodes are required to route and transmit data over a large distance.

3.2 System Boundaries

As shown in Figure 15, the system under test is a MANET. The component under test in this system is the routing protocol. Other components that make up the system are the mobile nodes, the data links, and the geographical area.

The nodes in the system transmit data using the specified routing protocol. This transmitted data is the input to the system. Data is sent from the source node to its destination node over the ad hoc network. The output of the system is measured by the data that arrives at the destination node. Total packets received, throughput, and average end-to-end (ETE) delay are the metrics collected to identify the characteristics of the different routing protocols.

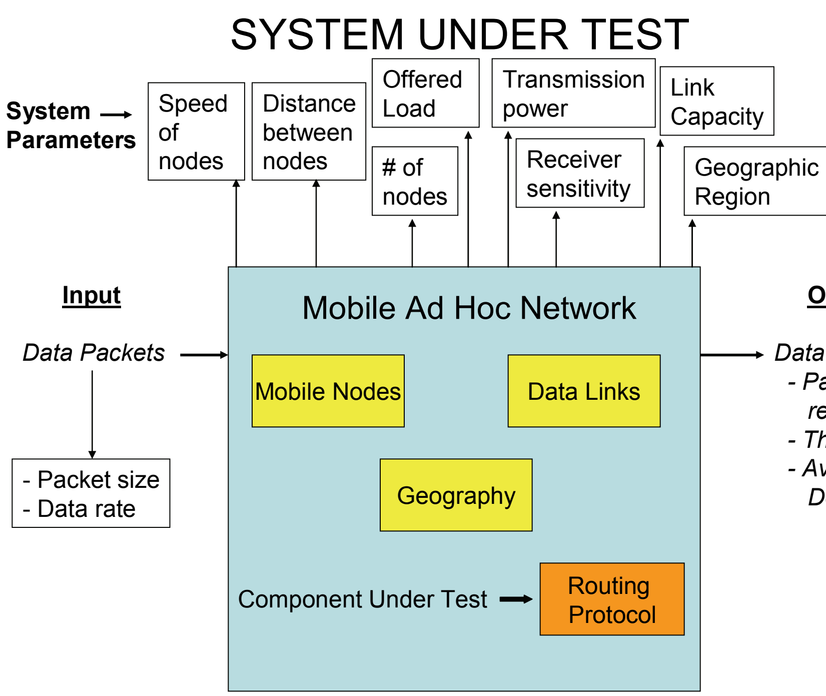

Figure 15. Block diagram of the system under test

The components of the system are identified, as well as the Component Under Test (CUT). The figure also shows the workload (input) and the system output as well as the system parameters.

3.3 System Services

The system offers one service, the transmission of data. The source transmits data while the destination receives data. When the destination receives packets through the network, successful transmission occurs. Failure occurs when data does not reach the destination. In the cases where the packets received does not equal the number of packets sent, the throughput is not equal to the data rate that is being transmitted from the source, or the ETE delays are observed to be inconsistent between different runs of the same experiment and different routing protocols, these cases are not considered failures, but will be observed and analyzed with respect to the network behavior and routing protocol behavior. A congested network and node mobility patterns could potentially cause order of magnitude differences in both throughput and average end-to-end delay. These results do not mean failure, but provide information on protocol behavior under given network scenarios.

3.4 Workload

The workload, or offered load, for the SUT is the data packets that are being transmitted from the source node to the destination node. Because the system is a network, the only measurable input is the data that enters the system. The input can be varied both in packet size and transmission rates, but the data packets themselves are the only workload to the system.

3.5 Performance Metrics

Before any metrics can be analyzed, the most important performance metric that must be observed is successful transmission of data across the network. The number of packets received at the destination is the metric measured to determine if the data is successfully traversing the network. If data packets are transmitted but no packets are received, the network fails. This may be due to routing protocol failure, link failure, network congestion, or physical limitations such as the speed of the mobile nodes or the distance that separates the nodes.

Throughput of the network is another metric measured. There is only one transmission in the simulation at one moment in time. Throughput is calculated by QualNet using

$$\text{Throughput} = \frac{(\text{Total\_bytes\_received} * 8)}{(\text{session\_finish} - \text{session\_start})} \quad (1)$$

where Total_bytes_received is the total number of bytes received at the destination, session_finish is the time at which the last packet is received at the destination (or the simulation time if the session is still open at the end of the simulation), and session_start is the time at which the first packet is received at the destination. Throughput is a measure of how efficiently the bandwidth is used.

Average ETE delay is another performance metric measured. Average ETE delay is defined as the time difference between when the packet is created at the source and when the packet is received at the destination and is calculated using

$$\text{Avg ETE delay} = \frac{\text{Destination\_total\_ETE\_delay}}{\text{Destination\_packets\_received}} \quad (2)$$

where Destination_packets_received is the total number of packets received at the destination, and Destination_total_ETE_delay is the sum of individual ETE delay for each of the data packets, where the individual ETE delay, Pkt_ETE_delay, for each packet is calculated using

$$\text{Pkt\_ETE\_delay} = \text{Sim\_time\_pkt\_rcvd} - \text{Sim\_time\_pkt\_created} \qquad (3)$$

where Sim_time_pkt_rcvd is the simulation time when the packet is received at the destination, and Sim_time_pkt_created is the simulation time when the packet is created at the source.

3.5.1 QualNet Statistics

The statistics generated by QualNet, while thoroughly defining network performance, must be understood in how they are generated. The metrics used in this study, average ETE delay, number of packets received, and throughput, are important to observing network performance, yet in QualNet, calculations are not correlated to one another. Throughput and average ETE delay results are independent of each other. Throughput and number of packets received results are also independent of each other. Simple examples can provide an understanding of QualNet generated statistics. Throughput and number of packets received, while similar metrics, do not always correspond in the same manner. For example, a high number of packets received does not always correlate to a high throughput, and a high throughput does not always correlate to high number of packets received. This can be seen through simple examples of QualNet calculations for both metrics. QualNet calculates the number of packets received as

$$\text{Packets received} = \frac{\text{(Total bytes received)}}{\text{(Number of bytes per packet)}} \quad (4)$$

The following examples represent arbitrary numbers to show the independent nature of the metrics.

In a simple example, if 1,000,000 bytes are received over the entirety of the experiment with a packet size of 50,000 bytes, the number of packets received is 20. When calculating throughput in the manner performed by QualNet, throughput is dependent upon the elapsed time required to transmit those 20 packets. In experiment A, if those 20 packets are transmitted over 20 seconds, the throughput is 400 Kbps. In experiment B, if those same 20 packets are transmitted over 200 seconds, the throughput is 40 Kbps. In both cases, the same number of packets were received at the destination, however, the elapsed time required in each case changed the throughput. This distinction must be noted to understand the results observed in this study.

Throughput and average ETE delay are also independent of each other. Using a simple example to identify this independence, the source transmits 20 packets (each packet consists of 50,000 bytes) at a rate of 1 packet per second and all 20 packets are received at the destination. Assuming that all packets are received in 220 seconds, simple analysis would conclude that

$$\text{Average ETE delay} = \frac{\text{220 seconds}}{\text{20 packets}} = \text{11 seconds/packet}$$

However, in QualNet, knowing when each packet arrived at the destination is required. Each individual packet ETE delay is added to a total ETE delay sum. Using our example above, in experiment A, if we assume that all 20 packets were received in 220 seconds, but the first packet was received at time = 1 second, but the second through 20^{th} packet were received at times = 202 seconds through 220 seconds, QualNet average ETE delay is calculated as

$$\text{Avg ETE delay} = \frac{\text{Sum of ETE delays}}{\text{Packets received}} = \frac{1 + (19 * 200)}{20} = 190.05 \text{ seconds/packet}$$

However, in experiment B, if we assume that all 20 packets were received in 220 seconds, but the first 19 packets were received with an average ETE delay of 1 second, at times = 1 second through 19 seconds, with the final packet being received at time = 220, QualNet would calculate average ETE delay as

$$\text{Avg ETE delay} = \frac{\text{Sum of ETE delays}}{\text{Packets received}} = \frac{(19*1) + 200}{20} = 10.95 \text{ seconds/packet}$$

In both cases, even with a large difference between average ETE delays, throughput remained the same,

$$\text{Throughput} = \frac{\text{Total bytes received * 8}}{\text{(Session\_finish – session\_start)}} = \frac{\text{8000000 bits}}{\text{(220 - 0) secs}} = 36364 \text{ bps}$$

By walking through these simple notional examples, it is shown that the QualNet-generated statistics used in this study, while describing performance accurately, are independent of one another.

3.6 Parameters

3.6.1 System

The system parameters are the characteristics of the system that, if changed, will affect the responses. The parameters of the SUT are: speed of the nodes, distance between the nodes, the number of nodes in the system, the injected background traffic on the system, the radio characteristics of the nodes, transmission power of the nodes, the receiver sensitivity of the nodes, the data link capacity, and the geography of the test region. Each of these parameters can change the performance of the routing protocols.

3.6.2 Workload

The workload of the system is the transmitted data packets. The workload parameters are the size of the data packets being transmitted and the rate of transmission of the data packets. The size of the data packets will affect the latency of the system – how long it takes for a packet to arrive at its destination, since transmission delay needs to be accounted for in ETE delay. ETE delay takes into account transmission delay, propagation delay, processing delay, and queuing delay and is calculated using

$$\text{Transmission delay} = \frac{\text{Packet size (bits)}}{\text{link capacity (bits per second)}} \qquad (5)$$

where Packet size is the size in bits of each packet transmitted, and link capacity is the maximum capacity in bits per second of the data link.

3.7 Factors

The factors are those parameters that are varied during the analysis. The factors for this study are the number of nodes in the network, the injected background traffic on the system, and the routing protocol. In the case of ZRP, the zone radius is a factor as well. The factors are outlined in Table 1.

The levels for the number of airborne nodes in the network are 3, 6, and 12 nodes. AFCA guidance indicates that a typical number of “heavy” aircraft, which is identified by the airborne nodes, in an area of this size would be 6 [AFCA06]. The levels represent a low, medium, and high density of airborne nodes determined by a factor of 2.

The levels for the injected background traffic are none and 1 Mbps. These levels are selected because of the different stress levels placed upon the 2 Mbps link capacity of the system. With no injected background traffic, the routing protocols can be observed operating in the large-area, high-speed mobile node network free of congestion. This enables observation of the routing protocol performance operating strictly under the mobility and size constraints of the network. With background traffic at 1 Mbps, the data is forced to travel through a congested network that is already operating at 50% capacity, raising the stress on the links to 70% capacity. When there is no background traffic in the system, there are only 2 ground nodes, the source node and the destination node. When background traffic is introduced to the system, 2 additional ground nodes are added to the network for modeling background traffic purposes.

The levels for the number of nodes in the network are 5, 7, 8, 10, 14, and 16 nodes. These numbers of nodes are the factorial combinations of the sum of the aircraft and ground nodes.

Four routing protocols are tested – AODV, DYMO, Fisheye, and ZRP. ZRP is tested using two levels (2, 3) of zone radius.

Table 1. System Factors

FACTORS	**LEVELS**
Number of Nodes	5, 7, 8, 10, 14, 16
- Aircraft Nodes	3, 6, 12
- Ground Nodes	2, 4
Injected Background Traffic	None, 1 Mbps
Routing Protocols	AODV, DYMO, FSR, ZRP
- ZRP Zone radius	2, 3

3.8 Fixed Parameters

The parameters of the study are listed below. Details of each parameter are addressed.

- Size and type of region
- Mobility pattern of the Airborne nodes
- Altitude of the Aircraft nodes
- Speed of the nodes
- Placement of Ground nodes
- Test data application
- Background traffic data application
- Data transmission rate
- Link capacity
- Physical radio model
- Transmission power and receiver sensitivity

Figure 16 is a simple depiction of the experiment setup. The size of region used in this study is a 500 mile by 500 mile area. The aircraft nodes traverse randomly throughout this region using the random waypoint model at a fixed speed of 500 miles per hour. The altitude of the aircraft is fixed at 30,000 feet. The speed and altitude are representative of the aircraft considered in this study –AWACS [Boe07], KC-135 [AFL07], and JSTARS [AFL07], as shown in Table 2.

Although the ground nodes are mobile nodes, they remain stationary throughout the tests. The ground nodes are those nodes transmitting and receiving the data. Relative to aircraft speeds, ground speeds are negligible. The placement of the source and destination nodes is arbitrarily selected such that a 500 mile separation between them exists. For the experiments performed in this research, the placement is centrally located along the left and right borders of the tested region (see Figures 16 and 17). The location of the nodes is irrelevant, but the distance separating the nodes is the motivation behind the node placement.

When the background traffic is added to the system, 2 additional ground nodes are used to model this traffic. These additional ground nodes are also stationary and are placed on the top and bottom borders of the tested region (see Figure 18). This placement was chosen such that traffic could be easily introduced to the network without providing "straight-line" hops to the destination. The goal of placing the additional ground nodes is to introduce traffic to the system while still forcing the test data to route through the aircraft to reach the destination. The background traffic is modeled by three separate variable bit rate (VBR) data transmission links, 2 links transmitting data at 360 Kbps and 1 link transmitting data at 280 Kbps, for a cumulative total of 1 Mbps. These transmission links are selected arbitrarily to introduce and route 1 Mbps of background traffic throughout the entire network. VBR data is representative of generic multimedia data. However, the ground nodes introducing the background traffic operate within the same range limitations as the source and destination nodes. If no aircraft are within line-of-sight communication range from the background traffic generating nodes, no background traffic is being injected into the network.

The test data is a constant bit rate (CBR) data application, transmitting packets of size 50K bytes at 1 second intervals, or 400 Kbps. This choice of transmission data is representative of generic multimedia data. Setting up the test data transmission as CBR and the background traffic as VBR is chosen because of QualNet statistics generation. QualNet measures the number of packets received and calculates throughput and average ETE delay at the destination for CBR data applications. A total of 2500 packets are transmitted, for a total of 1 GB of data. The data link capacity used in this experimentation is 2 Mbps. Packet size is chosen so that 20% of the bandwidth capacity is utilized by the test data application. As mentioned earlier, the background traffic adds additional stress to the 2 Mbps link capacity.

Table 2. Aircraft speed and altitude statistics

AIRCRAFT	CRUISE SPEED	ALTITUDE
KC-135	530 miles/hour	50,000 ft
E-8 JSTARS	390 – 510 nautical miles/hour	42,000 ft
E-3 AWACS	More than 500 miles/hour	More than 35,000 ft

The physical radio model, transmission power, receiver sensitivity, and antenna gains remain fixed. The radio model used is the 802.11b, using the 802.11 MAC protocol.

The transmission frequency used in these experiments is fixed at 120 MHz. This frequency is reserved for Aeronautical Mobile communications, as identified in the United States Frequency Allocations chart [USFA03].

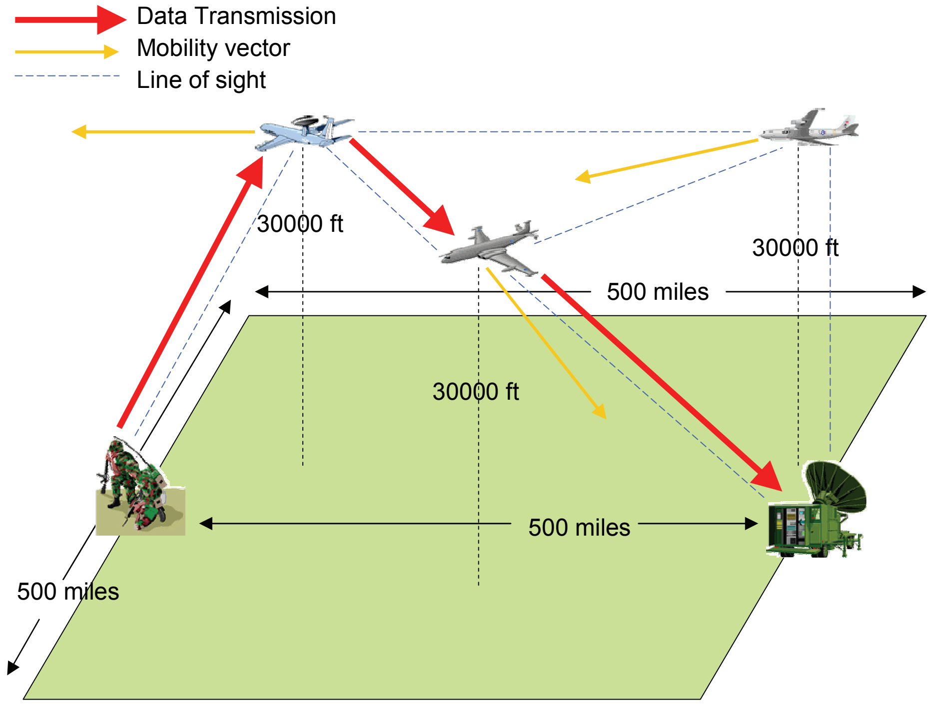

Figure 16. Experimental setup

3.9 Evaluation Technique

The system is evaluated using the QualNet 4.0 network simulator. Each routing protocol is compared against the others given the same simulation scenario.

3.10 Experimental Design

A full-factorial comparative objective experimental design is required to satisfy the goals of this study. Table 3 offers a factorial breakdown for the number of experiments. Each experiment will be performed 10 times to collect a better sampling of data. By testing 4 different routing protocols, of which ZRP is tested at 2 separate levels, with 2 separate injected background traffic levels, and 3 scenarios with differing aircraft node numbers, a total of 300 experiments are required.

Table 3. Factorial breakdown of number of experiments performed

FACTORS	LEVELS	NUMBER
Protocols	AODV, DYMO, FSR, ZRP (2, 3)	5
Injected Background Traffic	None, 1 Mbps	2
Aircraft Nodes	3, 6, 12	3
Samples	Seeds 1-10	10
Total experiments	5*2*3*10	300

This data allows the protocols to be evaluated against each other. It also allows insight into how each routing protocol performs under a given set of conditions. The full-factorial experiment gives insight into how the density of the network and the introduced background traffic affects the routing protocol performance. By determining the effects of these factors, conclusions about the performance of the four protocols can be made with confidence, albeit with the caveat "under these conditions." Comparative analysis of the protocols will be performed using the collected data. The performance of the routing protocols is compared against each other relative to number of aircraft nodes in the network and offered load placed upon the system. Plots of the comparative data are generated to view routing protocol average ETE delay, number of packets received, and throughput performance.

3.9.1 Experimental Testing

The purpose of this testing is to observe how the routing protocols perform in a large-area, high-speed mobile node MANET. Modeling this large-area MANET requires modifying physical and link layer parameters in the QualNet simulator. Understanding the details behind these physical and link layer parameters falls beyond the scope of this network layer study of routing protocol performance. By scaling the size of the area and speed of the mobile nodes such that they remain proportionate to that of a full-scale model, the performance of the protocols can still be properly observed. The experiments are scaled by a factor of 100, reducing the test region to a 5 mile by 5 mile space and the speed of the aircraft nodes to 5 mph. The impact of this scaled testing is only observed in the propagation delays of the data transmission, otherwise routing behavior remains the same. Compared to transmission delay (0.4 secs), propagation delay is negligible at 5 miles (27 μsecs) and 500 miles (2.7 msecs). Thus, the impact of scaling the test model is minimal when observing routing protocol performance.

Figures 17 and 18 provide snapshot views of the MANET modeled in QualNet. Both snapshots are of the scenario with 6 aircraft nodes, however, Figure 17 shows the scenario as run without background traffic, and Figure 18 shows the scenario as run with the background traffic placed on the system. The experiment parameters and values are identified in Table 4.

As mentioned above, the region and physical characteristics of the nodes have been scaled by a factor of 100. Therefore, the 500 mile by 500 mile region under study is modeled by a 5 mile by 5 mile region, or 8047 meters by 8047 meters in the QualNet simulation. The terrain is set up as a smooth, flat surface. The Two-Ray pathloss model [QUG06] is used. The wireless channel frequency is set to 120 MHz. The experiments are run for a period of 60 minutes, with data transmission occurring for 55 minutes. This period of time was selected due to the size of the area and the speed of the nodes. Over a 60 minute period, the aircraft nodes would be able to travel 500 miles (5 miles in the scaled model), or 458 miles (4.58 miles in a scaled model) over a 55 minute transmission period. This distance traveled offers a good sampling of how aircraft node movement affects the transmission links.

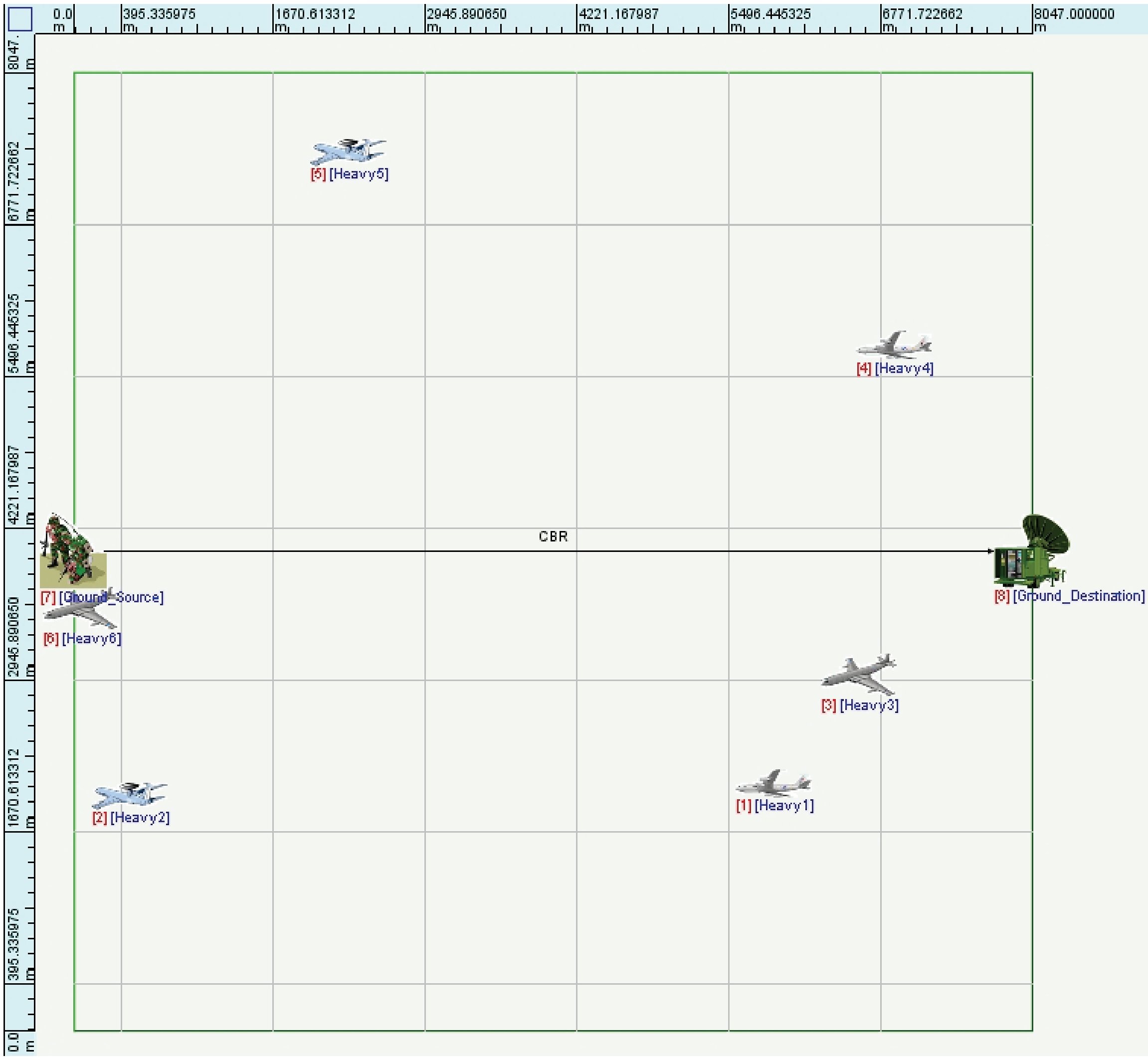

Figure 17. MANET image with 6 aircraft nodes without background traffic

The aircraft nodes are randomly placed, using QualNet's random node placement function with a seed of 10 for each configuration. This random placement function is only used to initially place the nodes. In each experiment, the initial placement of the nodes is the same. The ground nodes are placed such that the source and destination nodes are separated by 5 miles, representative of a 500 mile span. When background traffic is introduced into the network, additional ground nodes are statically placed.

Aircraft nodes move with random mobility using the Random Waypoint model [QUG06]. Aircraft speeds are set to 2.25 meters/sec, which is equivalent to 5 mph. This velocity is proportional to a 500 mph aircraft moving through a 500 mile by 500 mile region.

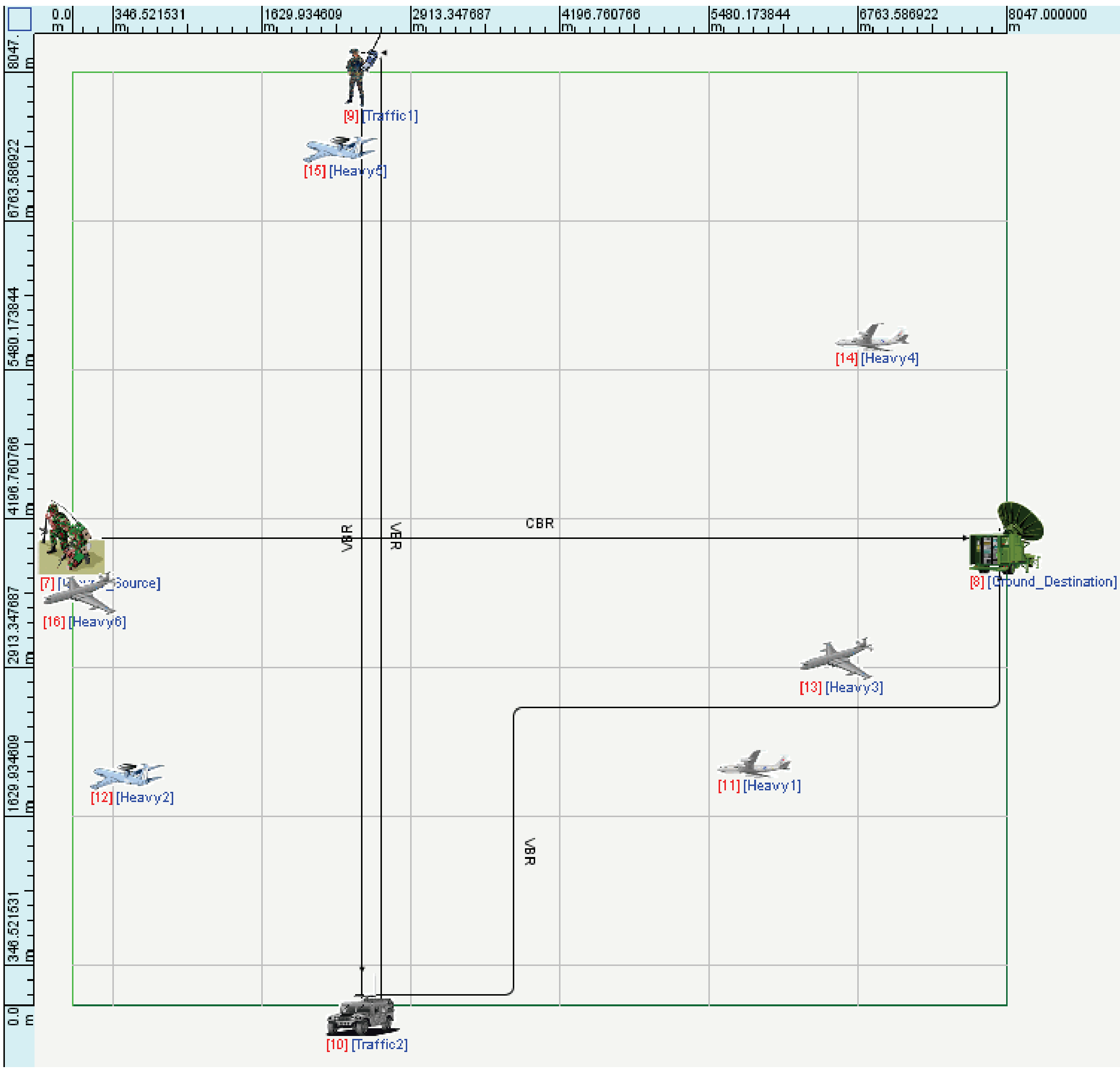

Figure 18. MANET image with 6 aircraft nodes with background traffic

Table 4. Fixed system parameters

PARAMETERS	FIXED VALUE
Size of region	5 miles x 5 miles (8047m x 8047m)
Terrain	Smooth, flat surface
Pathloss Model	Two-Ray
Altitude of nodes	0m
Wireless Channel Frequency	120MHz
Time period of experiments	60 minutes
Time period of test data flow	55 minutes
Placement of Aircraft nodes	Random (seed 10)
Placement of Ground nodes	Fixed, selected location placement
Distance between source – destination	5 miles (8047m)
Mobility of Aircraft nodes	Random Waypoint
Speed of Aircraft nodes	2.25 meters/sec
Data packet application	Constant Bit Rate
Packets transmitted	2500
Packet size	50KB (400,000 bits)
Rate of transmission	1 packet/sec
Background traffic application	Variable Bit Rate
Radio Type	802.11b
Data Link bandwidth	2 Mbps
Transmission Power	0.0 dB @ 1 Mbps 15.0 dB @ 2 Mbps 0.0 dB @ 6 Mbps 0.0 dB @ 11 Mbps
Receiver Sensitivity for Aircraft nodes	-93.0 dB @ 1 Mbps -89.0 dB @ 2 Mbps -87.0 dB @ 6 Mbps -83.0 dB @ 11 Mbps
Receiver Sensitivity for Ground nodes	-78.2 dB @ 1 Mbps -89.0 dB @ 2 Mbps 0.0 dB @ 6 Mbps 0.0 dB @ 11 Mbps
Antenna model	Omnidirectional
Antenna Gain for Aircraft nodes	29.8 dB
Antenna Gain for Ground nodes	20.8 dB
MAC protocol	802.11
MAC propagation delay for Aircraft nodes	18 µsec
MAC propagation delay for Ground nodes	10 µsec
Queue size	15 MB

The altitude of the aircraft nodes is set to zero. The flat surface scaled network models the 30,000 ft aircraft altitude line-of-sight requirements with the transmission power, receiver sensitivity, and antenna gain parameters. The transmission range of each mobile node can be calculated for line-of-sight distances as

$$D = (2*Ht_1)^{1/2} + (2*Ht_2)^{1/2} \quad (6)$$

where Ht_1 is the height of the transmitting antenna in ft, and Ht_2 is the height of the receiving antenna in ft, and D is the line-of-sight distance between them in miles [RDRE46]. Using (5), where Ht_1 and Ht_2 are both 30,000 ft, generates a line-of-sight range of 489.9 miles between the airborne nodes. If either Ht_1 or Ht_2 is set to zero representing the ground nodes, (5) yields a line-of-sight range of 244.95 miles between a ground node and an aircraft node. Within the scaled model, the 489.9 and 244.95 mile ranges becomes 7884 and 3942 meters, respectively. The 802.11b radios and antennas are modeled to communicate over these distances.

The 802.11b radio settings for transmission power and receiver sensitivity are set as follows:

- For aircraft nodes, the transmission power is set to 15.0 dB at the 2 Mbps setting while the transmission power at the 1, 6, and 11 Mbps settings are set to 0 dB. The receiver sensitivity is kept at the radio default values of -93.0 dB, -89.0 dB, -87.0 dB, and -83.0 dB for the 1, 2, 6, and 11 Mbps settings, respectively. The antenna gain is set to 29.8 dB. The aircraft nodes are able to transmit and receive data a maximum distance of 7884 meters.

- For ground nodes, the transmission power is set to 15.0 dB at the 2 Mbps setting while the transmission power at the 1, 6, and 11 Mbps settings are set to 0 dB. The receiver sensitivities are set to -78.2 dB, -89.0 dB, 0 dB, and 0 dB for the 1, 2, 6, and 11 Mbps settings, respectively. The antenna gain is set to 20.8 dB. The ground nodes are able to transmit and receive data a maximum distance of 3942 meters.

These settings are chosen because they model line-of-sight communication between the nodes on the scaled-model flat surface. These settings need to be adjusted to correctly model the effect the curvature of the earth plays in line-of-sight communications between nodes at different altitudes. These values were determined through trial and error experiments in QualNet. Simple experiments were set up to transmit data between 2 nodes over the ranges required for aircraft and ground nodes. Transmission power, receiver sensitivity, and antenna gain parameters were modified so that transmission would occur over the ranges required.

Because the 802.11b radio is chosen for this experiment, the 802.11 MAC protocol is used. For aircraft node and ground node transmission, MAC propagation delay is set to 18 and 10 microseconds, respectively. These values were determined through trial and error experiments in QualNet.

The queue sizes are set to 15 MB to restrict packet loss due to queue overflow.

3.10 Methodology Summary

This experiment answers the primary question of interest: What difference is observed in MANET performance when using a reactive, proactive, or hybrid routing protocol, specifically AODV, DYMO, Fisheye, and ZRP, under the large-area, high-speed mobile node network conditions?

This experiment provides ample results to draw conclusions from the data collected and analyzed. There are several possible conclusions that can be drawn with the data and analysis gathered from this experiment regarding hybrid and reactive routing protocols and the performance of each in comparison to the other. These results will provide an indication of how proactive, reactive, and hybrid routing protocols, specifically AODV, DYMO, Fisheye, and ZRP, perform under a given set of conditions.

IV. Analysis and Results

This chapter presents the results and analysis on the data collected from the experiments. Section 4.1 provides validation of the experiment model. Section 4.2 discusses general observations about the experiment results. Sections 4.3 and 4.4 present the analysis and results. Section 4.5 concludes with a summary of the analysis and results.

4.1 Validation of Experiments

The constraints imposed by the selection of distance, node placement, and communication parameters for the modeled MANET make it is impossible for communication to occur from source to destination in fewer than 3 hops. This is shown in Figure 19. Each ground node is able to transmit a maximum of 3942 m and can only receive communication from an aircraft that is a maximum distance away of 3942 m. A 2-hop communication from ground node to ground node only covers a distance of 7884 m. This does not reach the distance of 8047 m separating the source and destination. As explained in Chapter 3, this was modeled to take into account curvature of the earth in a 500 mile region, given aircraft at 30,000 feet.

An ideal transmission should take 3 hops. This behavior is observed in the data gathered from the experiments. By observing the Average ETE Delay from the AODV experiments run with 3, 6, and 12 aircraft nodes with no background traffic (Table 5), the average ETE delay demonstrates this minimum hop count.

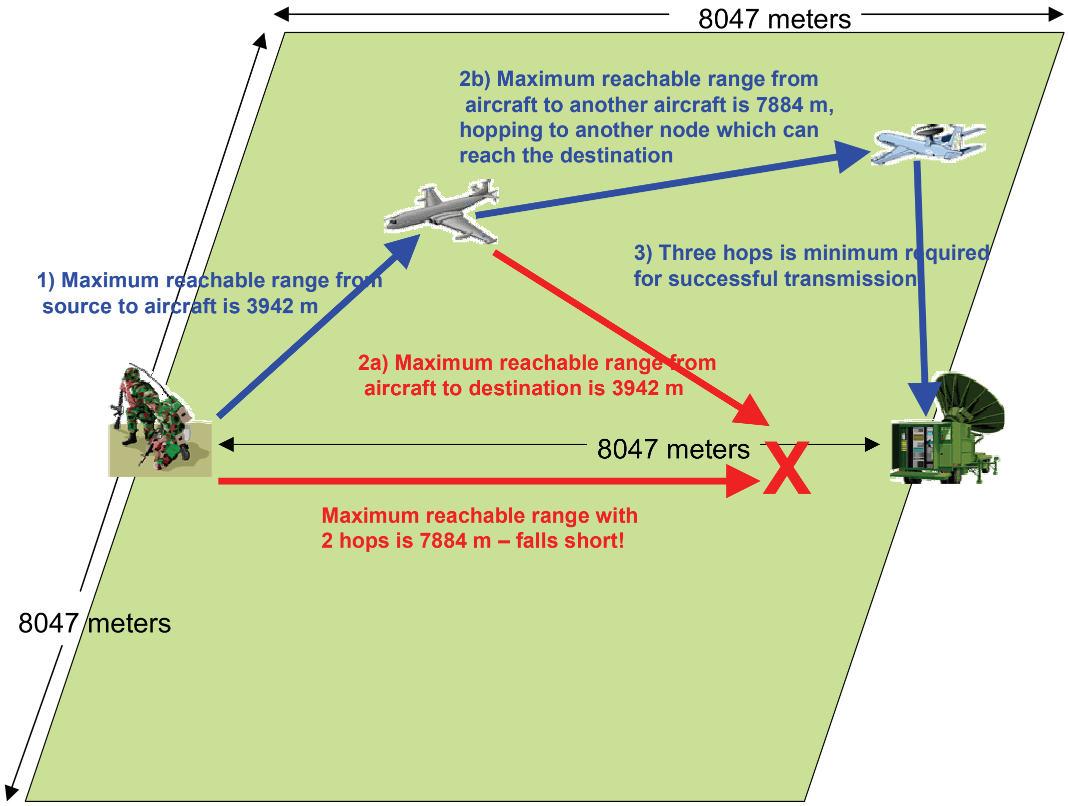

Figure 19. Minimum required hops from source to destination

Average ETE delay is calculated as

$$\text{Avg ETE Delay} = \text{Delay}_{\text{Transmission}} + \text{Delay}_{\text{Propagation}} + \text{Delay}_{\text{Queuing}} + \text{Delay}_{\text{Processing}} \quad (7)$$

where $\text{Delay}_{\text{Transmission}}$ is the transmission delay, $\text{Delay}_{\text{Propagation}}$ is the propagation delay, $\text{Delay}_{\text{Queuing}}$ is the queuing delay, and $\text{Delay}_{\text{Processing}}$ is the processing delay.

Using (6) and calculating the values for transmission and propagation delay, it can be shown that for an ideal 3-hop transmission,

$$\text{Avg ETE Delay} = 3 \text{ hops} * \frac{\text{trans rate}}{\text{link capacity}} + \frac{\text{distance}}{\text{speed of light}} + \text{Delay}_{\text{Queing}} + \text{Delay}_{\text{Processing}}$$

$$\text{Avg ETE Delay} = 3 * \frac{(400 \text{ kbps})}{(2 \text{ Mbps})} + \frac{8047\text{m}}{(3*10^{8} \text{ m/s})} + \text{Delay}_{\text{Queing}} + \text{Delay}_{\text{Processing}}$$

resulting in

$$\text{Avg ETE Delay} = 0.600027 + \text{Delay}_{\text{Queing}} + \text{Delay}_{\text{Processing}} \text{ secs}$$

Making the assumption that the queuing delay and processing delay in an ideal transmission are negligible, the average ETE delay in this ideal transmission is calculated to be no less than 0.600027 seconds. Observing AODV average ETE delays in the range of 0.77 (minimum ETE delay observed for 3 aircraft) to 0.93 seconds (max ETE delay observed for 12 aircraft), shown in Table 5, this data indicates that transmissions are occurring throughout the network with a minimum of 3 hops, validating that the experiment data is near what is calculated. If average ETE delays were observed to be less than 0.600027 seconds or larger than this value by an order of magnitude, the experiment data would be subject to question regarding its accuracy. By validating the average ETE delay data calculated by QualNet, the packets received and throughput data are assumed to be properly calculated as well.

Table 5. AODV average ETE delays (s) for networks with no background traffic

3 Aircraft	6 Aircraft	12 Aircraft
0.806735554	0.850298768	0.906868464
0.779855711	0.842785795	0.929799574
0.908286515	0.869085711	0.918290572
0.815592495	0.860289576	0.929903369
0.841868124	0.843994741	0.887220503
0.804378913	0.838481036	0.926910109
0.791550499	0.862389321	0.896473181
0.807484045	0.842635333	0.919133425
0.814423136	0.842813704	0.880789587
0.81117983	0.868789773	0.917884899

4.2 General Observations

4.2.1 ZRP Observations

Experiments were performed with ZRP using two different zone radii (2, 3). Each ZRP experiment was set up to use Bordercast Resolution Protocol as its search mechanism[QUG06][HPS01c]. However, ZRP results for both radius values were identical.

The results should be similar, but a distinction between the results of the two radii was expected. As discussed in Section 4.1, 3 hops are required to transmit data from the source to destination. By using a zone radius of 3, the destination node should be included in the source node's zone. This would indicate that ZRP would be operating primarily using its proactive routing capabilities. Using a zone radius of 2, while much of the area can be covered within the source node's zone, the source can never reach the destination with 2 hops, requiring more use of ZRP's reactive routing capabilities. Therefore, a difference in performance was expected between the 2 radii configurations.

4.2.2 DYMO Observations

While running the experiments for the configurations with 6 and 12 aircraft and the background traffic included in the network, with DYMO as the routing protocol, QualNet generated an executable error and shut down. Because of this error, no data was collected from the 6-aircraft configuration in the 10 experiments run, and only 2 experiments (out of 10 total) were successful in the 12-aircraft configuration.

This behavior was repeated multiple times and was only observed in these 2 configurations using the DYMO routing protocol. Because DYMO is a new routing protocol under development, its implementation in QualNet was observed to have flaws. Because it is a recently developed routing protocol, DYMO implementation is a current research endeavor.

The effort in this study did not include coding research into the QualNet modeling libraries to understand the programming logic behind the DYMO implementation.

4.3 Data Analysis

Testing was performed on 6 different network configurations using each routing protocol for each configuration (Table 6).

Table 6. MANET configurations

Configuration	# of Aircraft	Background Traffic	# of Ground Nodes	Total # of Nodes
1	3	None	2	5
2	3	1 Mbps	4	7
3	6	None	2	8
4	6	1 Mbps	4	10
5	12	None	2	14
6	12	1 Mbps	4	16

4.3.1 Data Excluded from Analysis

Due to observed results, data from the configuration with 3 aircraft nodes and no background traffic, shown in Figure 20, is excluded from analysis. As shown in Table 7, under this configuration, essentially no packets reach the destination.

One possible explanation for this behavior is due to the size, distance, and communication range parameters chosen for this study. Because a minimum of 3 hops are required for data to traverse the network, the location of the aircraft and their mobility patterns are primary factors for the lack of data making it through the network. Using only 3 aircraft moving randomly throughout the area, there is a much lower probability (than networks with a larger number of nodes) that at any given time, 1 aircraft is within communication range of the source node and 1 aircraft is within communication range of the destination node.

As more nodes are added to the network, more packets are able to reach the destination. Case and point, when background traffic is introduced with the addition of 2 grounds nodes (Figure 21) more packets successfully reach the destination (Table 9).

Figure 20. MANET with 3 aircraft (no background traffic)

Table 7. Packets received for 3-aircraft MANET with no background traffic

AODV	DYMO	Fisheye	ZRP
1	1	--	1
1	1	--	2
1	1	2	1
1	1	3	--
1	1	2	2
1	--	1	--
2	--	--	2
2	2	2	1
1	1	1	--
1	1	3	2

Because an extremely low number of data reaches the destination in the 3-aircraft configuration with no background, throughput results are highly inaccurate. Table 8 lists the throughput observed at the destination for each experiment run with 3 aircraft and no offered load. The throughput results are consistent with the packets received results. Understanding how QualNet calculates throughput, as discussed in Section 3.5, sheds light on the erratic nature of the throughput observed for low numbers of data packets received. If only 1 packet is received, throughput essentially results in an infinite value, or bad data. As the number of packets reaching the destination increases, the throughput calculation stabilizes and becomes more consistent.

For example, running simple throughput calculations using packets received observed in Table 7 and an estimate of 1 sec as the average ETE delay results in:

- 1 packet received,

(Session_finish = session_start)

$$\text{Throughput} = \frac{50000 * 8}{0} = \text{Infinite (bad data)}$$

- 2 packets received,

(Session_finish – session_start = 1 transmission period = 1 sec)

$$\text{Throughput} = \frac{100000 * 8}{1 \text{ sec}} = 800 \text{ kbps}$$

- 3 packets received,

(Session_finish – session_start = 2 transmission periods = 2 sec)

$$\text{Throughput} = \frac{150000 * 8}{2 \text{ secs}} = 600 \text{ kbps}$$

- 4 packets received,

(Session_finish – session_start = 3 transmission periods = 3 secs)

$$\text{Throughput} = \frac{200000 * 8}{3 \text{ secs}} = 533.33 \text{ kbps}$$

In this manner, it is seen that as the number of packets received increases, the value for throughput stabilize and becomes more accurate. This becomes evident when the additional ground nodes are introduced with the background traffic (Table 10). If data is being sent from the source at 400 kbps, the maximum throughput that can be observed at the destination is 400 kbps. Throughput calculations that generate values higher than this are obviously inaccurate. The examples above show for a low number of packets that reach the destination, throughput values generated by QualNet are highly inaccurate. But, for extremely low numbers of packets reaching the destination, throughput values are inaccurate. Table 11 shows that as the number of packets received increases, the percentage of error observed in throughput decreases.

Table 8. Throughput (bps) for 3-aircraft MANET with no background traffic

AODV	DYMO	Fisheye	ZRP
0	115	--	115
115	0	--	795227
114	0	394053	114
0	0	604662	--
115	0	810519	848441
0	--	114	--
819920	--	--	395912
804777	229	405053	0
0	0	115	--
115	115	601595	229

Table 9. Packets received for 3-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
156	--	72	90
545	559	129	218
581	552	213	298
205	226	--	76
729	687	330	417
221	--	26	55
724	781	637	647
417	377	122	148
147	--	99	190
410	--	120	137

Table 10. Throughput (bps) for 3-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
17947	--	8308	10419
63006	64527	14890	25200
66835	63481	24537	34261
23623	26012	--	8880
83836	79097	56531	58165
25444	--	2999	6343
83261	125009	127243	104023
47993	43355	14570	17182
16901	--	11404	21932
47147	--	13800	15768

Table 11. Percent error in throughput as the number of packets received increases

Packets Received	Calculated Throughput (bps)	Ideal Throughput (bps)	% Error
1	Infinite	400,000	Infinite
2	800,000	400,000	100%
5	500,000	400,000	25.0%
10	444,444	400,000	11.1%
50	408,163	400,000	2.04%
100	404,040	400,000	1.01%
500	400,802	400,000	0.20%
1000	400,400	400,000	0.10%

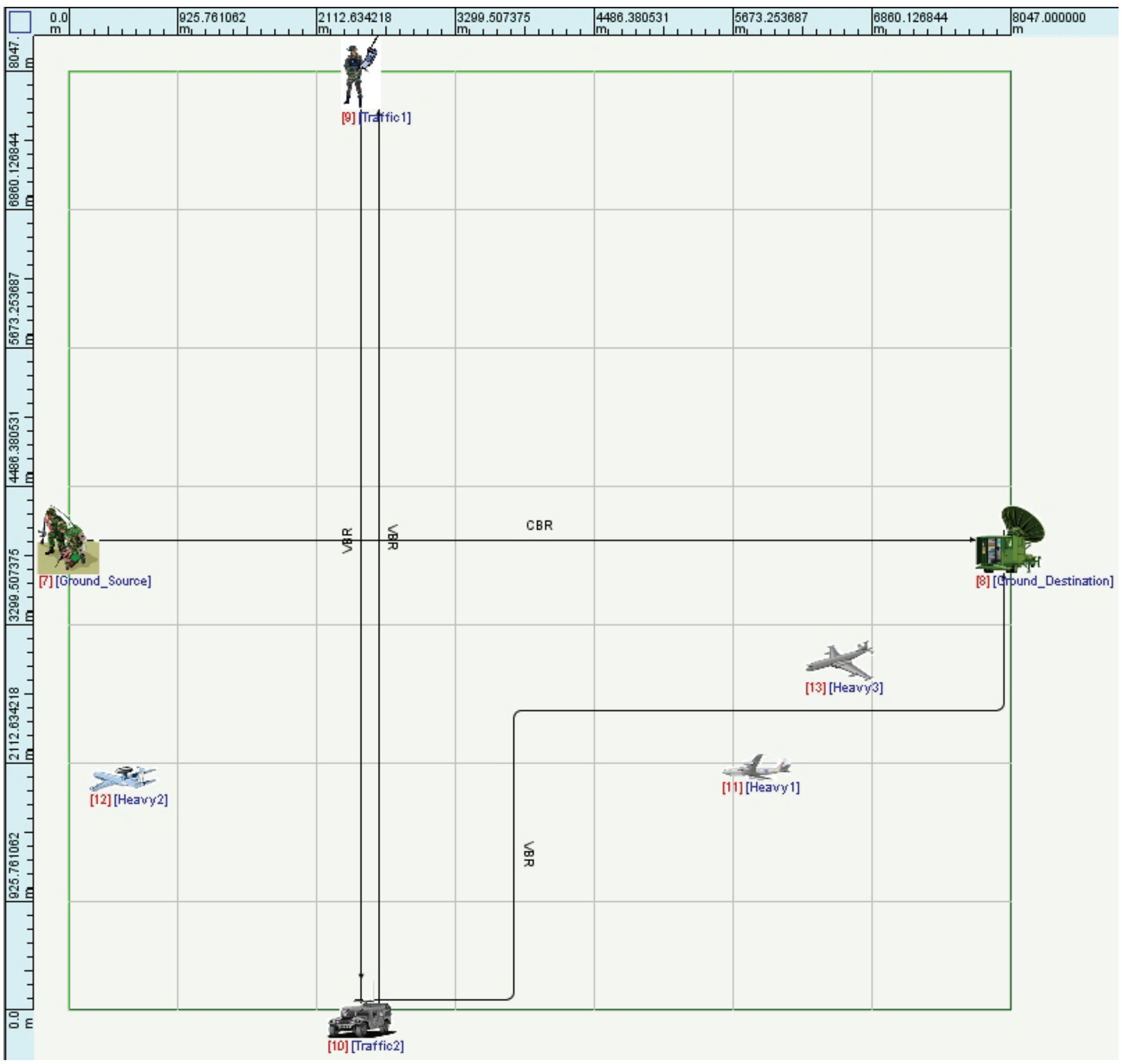

Figure 21. MANET with 3 mobile nodes (background traffic included)

4.3.2 Successful Experimentation

Ten experiments using different seeds were run with each routing protocol within each network configuration. However, not each experiment provided successful results. Successful transmission, described in Chapter 3, occurs when the destination receives data packets from the source. When an experiment failed, no data was able to be collected. Using the network configurations identified in Table 6, Table 12 shows the success rate with each routing protocol and network configuration. A 100% success rate occurs when 10 out of 10 experiments were successful. Configuration 1 data is not included, and DYMO shortcomings are discussed above in Section 4.2.

Table 12. Experiment success rates

Configuration	AODV	DYMO	Fisheye	ZRP
2	100%	60%	90%	100%
3	100%	100%	100%	100%
4	100%	0%	100%	100%
5	100%	100%	100%	100%
6	100%	20%	100%	80%

AODV performed successfully 100% of the time, with Fisheye and ZRP displaying successful performance over a high percentage of the experiments. These results offer a good sampling of data. DYMO performed successfully 100% of the time under 2 configurations, but the sampling of data for each of the 3 configurations with the background data included provide a marginal or poor sampling of data.

4.4 Analysis of Performance

The average ETE delay, number of packets received, and throughput results are the metrics collected and analyzed. Network responses are analyzed against the three factors in this study: protocol selection, number of aircraft nodes, and level of background traffic.

4.4.1 Analysis of Average ETE Delay

The general linear model is used to perform the ANOVA. The ANOVA model is set up with the average ETE delay as the response, where protocol, aircraft levels, and background traffic level as are identified as the predictors, along with their two and three-way interactions. Results of the ANOVA are shown in Table 13.

Table 13. ANOVA results for average ETE delay

Source	DF	Seq SS	% Variance
Protocol	3	1,490,905	20.0424%
Number of Aircraft	2	71,341	0.959%
Background Traffic	1	1,881,962	25.2995%
Protocol*Number of Aircraft	6	82,647	1.111%
Protocol*Background Traffic	3	1,121,960	15.0826%
Number of Aircraft* Background Traffic	2	4,076	0.0548%
Protocol*Number of Aircraft* Background Traffic	6	4,749	0.0638%
Error	151	2,781,106	37.3868%
Total	174	7,438,746	

The introduction of background traffic generates the highest level of average ETE delay variance with 25.3% across 1 degree of freedom. Protocol choice also has a large impact on average ETE delay with a variance of 20.04% across 3 degrees of freedom. The two-way interaction between the addition of background traffic and the choice of protocol generates a variance of 15.1% across 3 degrees of freedom. The variance generated by the number of aircraft (0.96% across 2 degrees of freedom), the two-way interaction between protocol choice and number of aircraft (1.11% across 6 degrees of freedom), the two-way level interaction between number of aircraft and background traffic (0.05% across 2 degrees of freedom), and the three-way interaction between protocol choice, number of aircraft, and background traffic (0.06% across 6 degrees of freedom) are all small enough to be negligible.

The ANOVA analysis used 175 pieces of test data, identified as *n* observations. These pieces of information are used to estimate factors or variability, and each item equates to 1 degree of freedom. Because the mean is defined as 1 factor that needs to be estimated, this accounts for the 174 total degrees of freedom, *n*-1, in the ANOVA results. The degree of freedom for each factor is its number of levels minus 1. The degrees of freedom for each 2- and 3-way interaction between the factors is calculated by multiplying the degrees of freedom for each factor together. The number of degrees of freedom for error is calculated by taking the total degrees of freedom and subtracting the degrees of freedom accounted for by the factors and their interactions. In these results, this leaves 151 degrees of freedom for error. For average ETE delay, error accounts for a 37.39% variance. But, when spreading that across 151 degrees of freedom, each degree of freedom for error accounts for 0.247% variance, which is very small. [Dal03]

Figure 22 is an interval plot of the average ETE delay versus the routing protocol. This plot shows the 95% confidence interval centered about the mean for each routing protocol. Table 14 lists the protocols, their means, and the ranges of the 95% confidence interval. Because there is no overlap of confidence intervals between AODV and

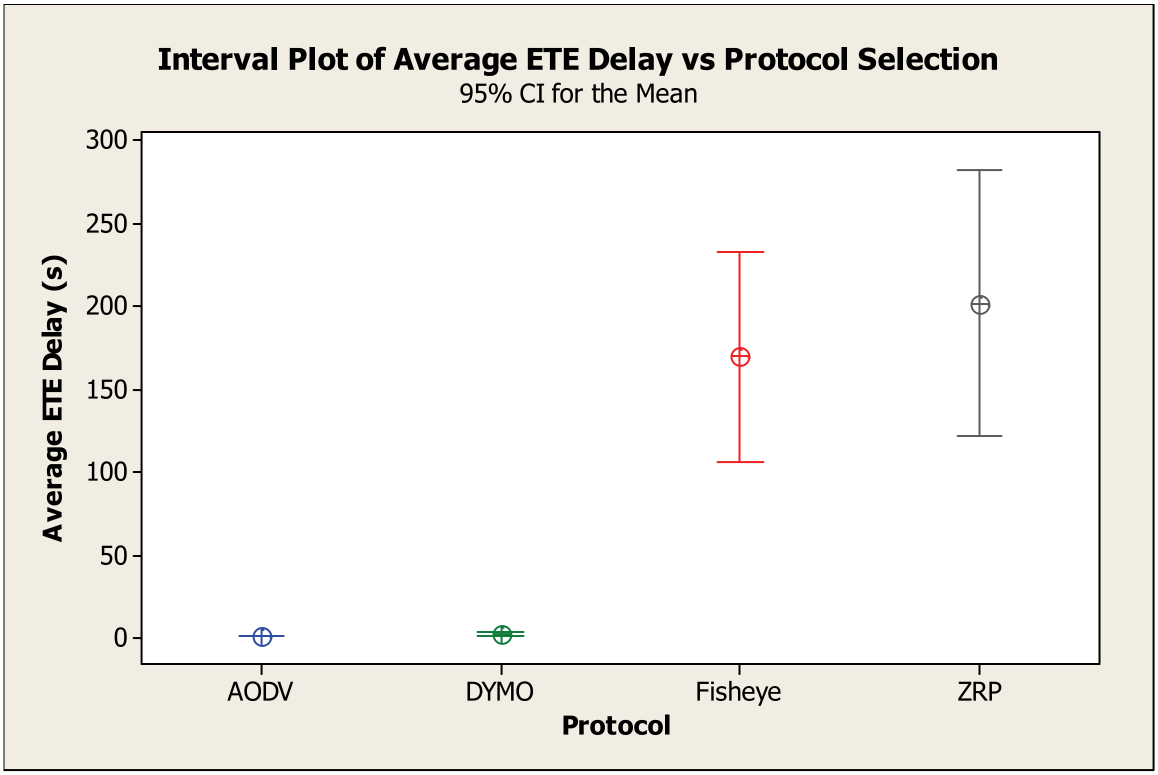

Figure 22. Interval plot of average ETE delay versus routing protocol

DYMO, AODV clearly performs with the lowest average ETE delays. Because the mean values for Fisheye and ZRP fall within the confidence intervals of each other, their results are not significantly different, although they do perform well below AODV and DYMO.

Fisheye and ZRP mean average ETE delays (169.7 and 201.9 secs) are much greater than those observed by AODV (1.2 secs) and DYMO (2.1 secs). Potential causes of these much higher delays could be a result of 1) queuing delays, as proactive and hybrid routing protocols do generate more overhead traffic, 2) an increased number of hops, as the routing tables are continually updated within the network, data is being transmitted back and forth between aircraft in an attempt to reach the destination, or 3) a combination of both.

Table 14. Average ETE delay vs routing protocol 95% confidence intervals

Routing Protocol	Mean (s)	95% Confidence Interval
AODV	1.17304	1.07861 – 1.26747
DYMO	2.14284	1.27062 – 3.01507
Fisheye	169.721	106.049 – 233.393
ZRP	201.908	121.668 – 282.148

Figure 23 is an interval plot of the average ETE delay versus the number of aircraft. This plot shows the 95% confidence interval centered about the mean for each level of aircraft. Table 15 lists the aircraft levels, their means, and the ranges of the 95%

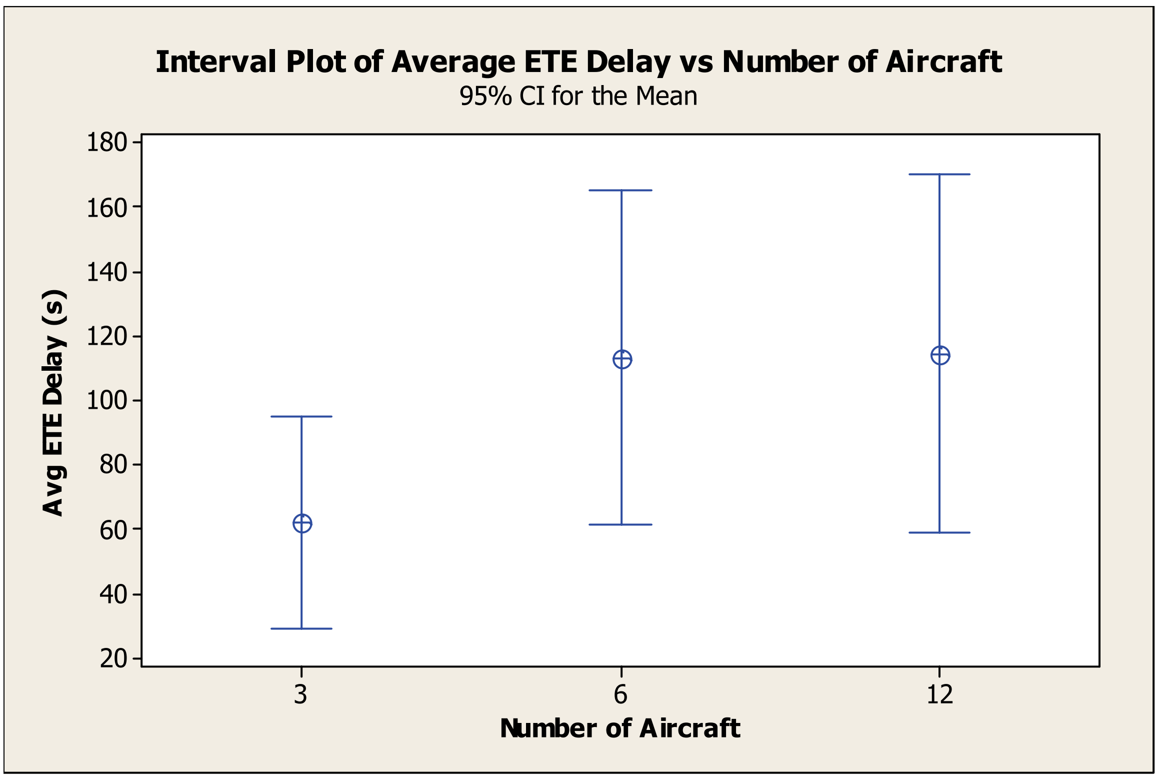

Figure 23. Interval plot of average ETE delay versus number of aircraft

confidence interval. Because the confidence intervals overlap among all 3 levels, and the means fall within the confidence intervals, the average ETE delay results are not significantly different between 3, 6, and 12 aircraft.

Although the average ETE delay means show large differences (greater than 50 seconds) between the 3-aircraft level and the 6- and 12-aircraft levels, the confidence interval analysis shows that there is no significant difference in average ETE delay between the levels of aircraft.

Table 15. Average ETE delay vs number of aircraft 95% confidence intervals

Number of Aircraft	Mean (s)	95% Confidence Interval
3	62.1357	29.0776 – 95.1937
6	113.366	61.3692 – 165.364
12	114.8012	58.8012 – 170.232

Figure 24 is an interval plot of the average ETE delay versus the level of background traffic. This plot shows the 95% confidence interval centered about the mean for each level of background traffic. Table 16 lists the background traffic levels, their

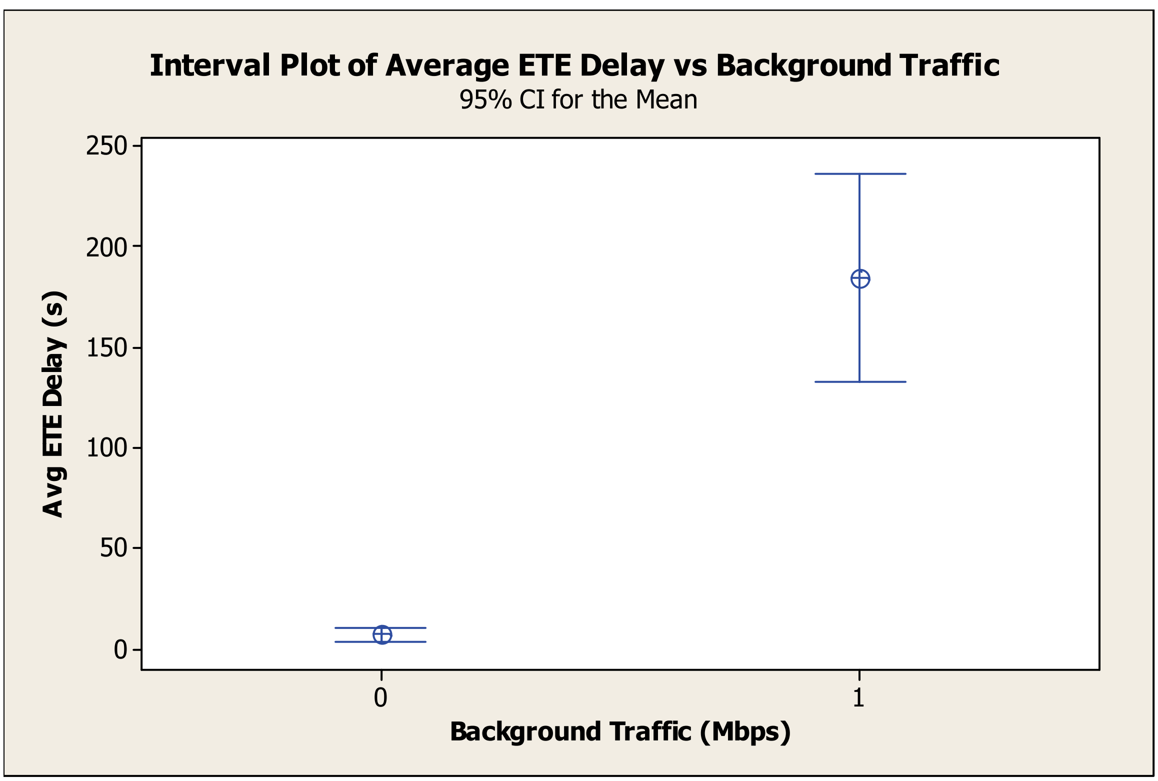

Figure 24. Interval plot of average ETE delay versus level of background traffic

means, and the ranges of the 95% confidence interval. The confidence intervals do not overlap between the 2 levels, therefore, it is clear to see that the addition of 1 Mbps background traffic impacts the average ETE delay performance.

The mean average ETE delay for configurations with no background traffic is 6.89 seconds, but when background traffic is added to the configurations, the mean delay increases to 185 seconds. The addition of 1 Mbps background traffic to the 2 Mbps link places a much heavier requirement on each of the airborne routers, increasing the queuing delay as the data is routed throughout the network. Average ETE delay is the summation of the transmission delay, propagation delay, queuing delay, and processing delay. The transmission, propagation, and processing delays are independent of the amount of traffic in the network. However, queuing delays are dependent upon the amount of traffic in the network, and accounts for the large increases seen when background traffic is introduced to the system.

Table 16. Average ETE delay vs background traffic 95% confidence intervals

Background Traffic	**Mean (s)**	**95% Confidence Interval**
None	6.88758	3.19141 – 10.5837
1 Mbps	185.006	133.372 – 236.640

4.4.2 Analysis of Number of Packets Received

The general linear model is used to perform the analysis of variance (ANOVA). The ANOVA model is set up with the number of packets received as the response, where protocol, aircraft levels, and background traffic level as are identified as the predictors, along with their two and three-way interactions. Results of the ANOVA are shown in Table 17.

The introduction of background traffic generates the highest level of number of packets received variance with 33.78% across 1 degree of freedom. Protocol choice also has a large impact on number of packets received with a variance of 41.39% across 3 degrees of freedom. The two-way interaction between the addition of background traffic and the choice of protocol generates a very small variance of 4.46% across 3 degrees of freedom. While random error shows an impact on the number of packets received (17.45% variance), this is spread across 151 degrees of freedom, making the error for each degree of freedom very small. The variance generated by the number of aircraft (1.55% across 2 degrees of freedom), the two-way interaction between protocol choice and number of aircraft (1.23% across 6 degrees of freedom), the two-way level interaction between number of aircraft and background traffic (0.02% across 2 degrees of freedom), and the three-way interaction between protocol choice, number of aircraft, and background traffic (0.11% across 6 degrees of freedom) are all small enough to be negligible.

Figure 25 is an interval plot of the number of packets received versus the routing protocol. This plot shows the 95% confidence interval centered about the mean for each routing protocol. Table 18 lists the protocols, their means, and the ranges of the 95% confidence interval. The number of packets received is the cumulative packets received at the destination over the entire 60 minute experiment. AODV and DYMO perform better than Fisheye and ZRP. However, because AODV and DYMO have overlapping confidence intervals without the mean of either falling in the confidence interval of the other, and the same occurs between Fisheye and ZRP, t-tests are used to indicate which routing protocol is the better performer between the two overlapping pairs.

Table 17. ANOVA results for number of packets received

Source	**DF**	**Seq SS**	**% Variance**
Protocol	3	5,950,399	41.3891%
Number of Aircraft	2	222,614	1.5484%
Background Traffic	1	4,856,081	33.7774%
Protocol*Number of Aircraft	6	177,327	1.2334%
Protocol*Background Traffic	3	641,233	4.4602%
Number of Aircraft* Background Traffic	2	3,114	0.0217%
Protocol*Number of Aircraft* Background Traffic	6	16,953	0.1179%
Error	151	2,509,018	17.4519%
Total	174	14,376,737	

The data being analyzed and compared are unpaired observations. The observations between the different levels of the factors have no direct correspondence between the pairs of measurements. To properly analyze these non-corresponding measurements, confidence intervals for the mean of differences using t-tests are calculated. This confidence interval is calculated using

$$\text{Confidence interval} = x_1 - x_2 \pm t_{\alpha/2;v} * \left(s_1^2 / n_1 + s_2^2 / n_2 \right)^{1/2} \quad (8)$$

where x_1, s_1, and n_1 are the mean, standard deviation and number of observations of system 1; x_2, s_2, and n_2 are the mean, standard deviation, and number of observations of system 2; t is the t-distribution with v degrees of freedom; where $\alpha/2$ is calculated

$$\alpha/2 = \frac{(100 - \%\text{ confidence interval})}{2} \tag{9}$$

and v is calculated using

$$v = \frac{\left(s_1^2 / n_1 + s_2^2 / n_2 \right)^2}{\left(s_1^4 / (n_1^2(n_1 - 1)) + s_2^4 / (n_2^2(n_2 - 1)) \right)} \tag{10}$$

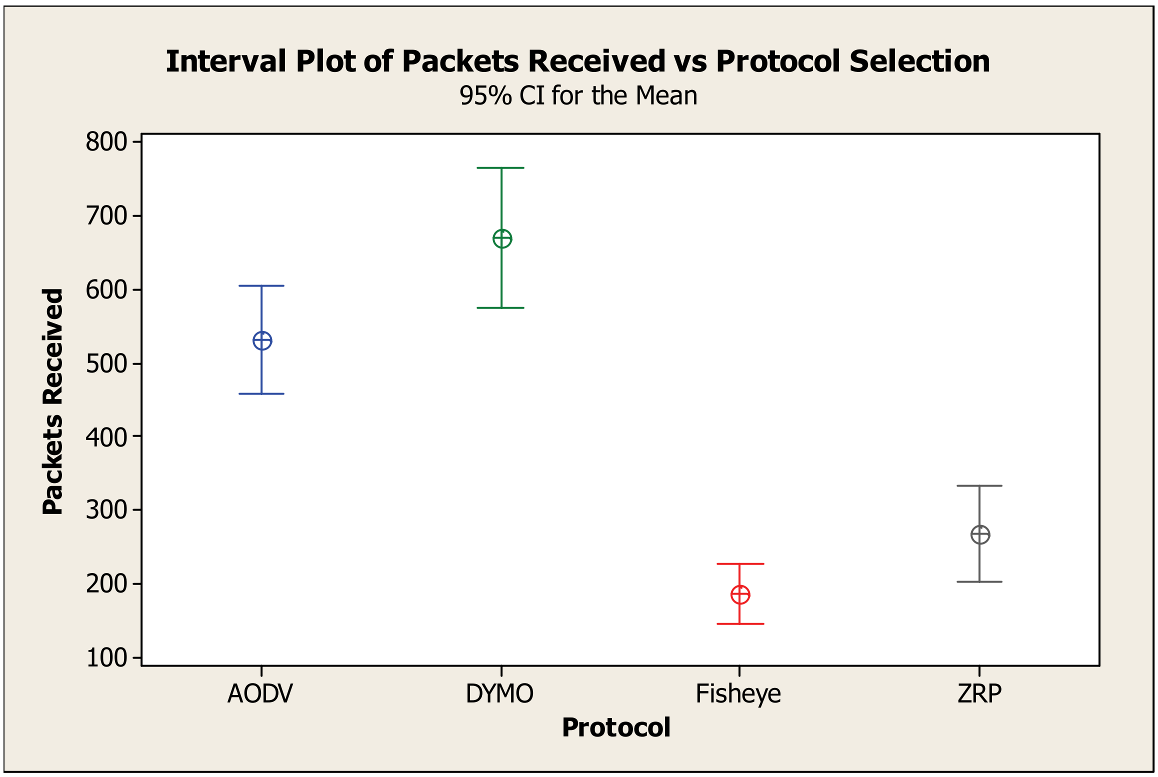

Figure 25. Interval plot of number of packets received versus routing protocol

Confidence intervals for the mean of differences are bounded around zero. If these confidence intervals contain zero, then there is no statistically significant difference between the two systems. However, if these confidence intervals do not contain zero, there is a statistically significant difference between the two systems.

Results of the t-test for AODV and DYMO generate a confidence interval of [-647.6, 370.5]. Because this confidence interval contains 0, the performance between AODV and DYMO is not significantly different. Results of the t-test for Fisheye and ZRP generate a confidence interval of [-157.823, -4.1093]. Because this confidence interval does not contain 0, Fisheye and ZRP performance is significantly different.

Table 18. Number of packets received vs routing protocol 95% confidence intervals

Routing Protocol	**Mean**	**95% Confidence Interval**
AODV	531.66	456.889 – 606.431
DYMO	670.214	574.966 – 765.462
Fisheye	186.388	145.201 – 227.574
ZRP	267.354	201.485 – 333.223

Figure 26 is an interval plot of the number of packets received versus the number of aircraft. This plot shows the 95% confidence interval centered about the mean for each level of aircraft. Table 19 lists the aircraft levels, their means, and the ranges of the 95% confidence interval. The 6-aircraft and 12-aircraft confidence intervals overlap with the means falling within the confidence interval. The same can be observed between the 3-aircraft and 12-aircraft confidence intervals. This indicates no significant difference between these two sets of comparisons. However, the confidence intervals of the 3 and 6-aircraft levels overlap without the means falling within these intervals. A t-test is performed to compare this significance. Results of the t-test for 3 and 6-aircraft levels generate a confidence interval of [-187.36, 20.3004]. Because this confidence interval contains 0, the performance between the 3 and 6-aircraft levels is not significantly different.

Table 19. Packets received vs number of aircraft 95% confidence intervals

Number of Aircraft	Mean	95% Confidence Interval
3	324.029	244.320 – 403.737
6	407.557	338.834 – 476.281
12	392.071	318.076 – 466.067

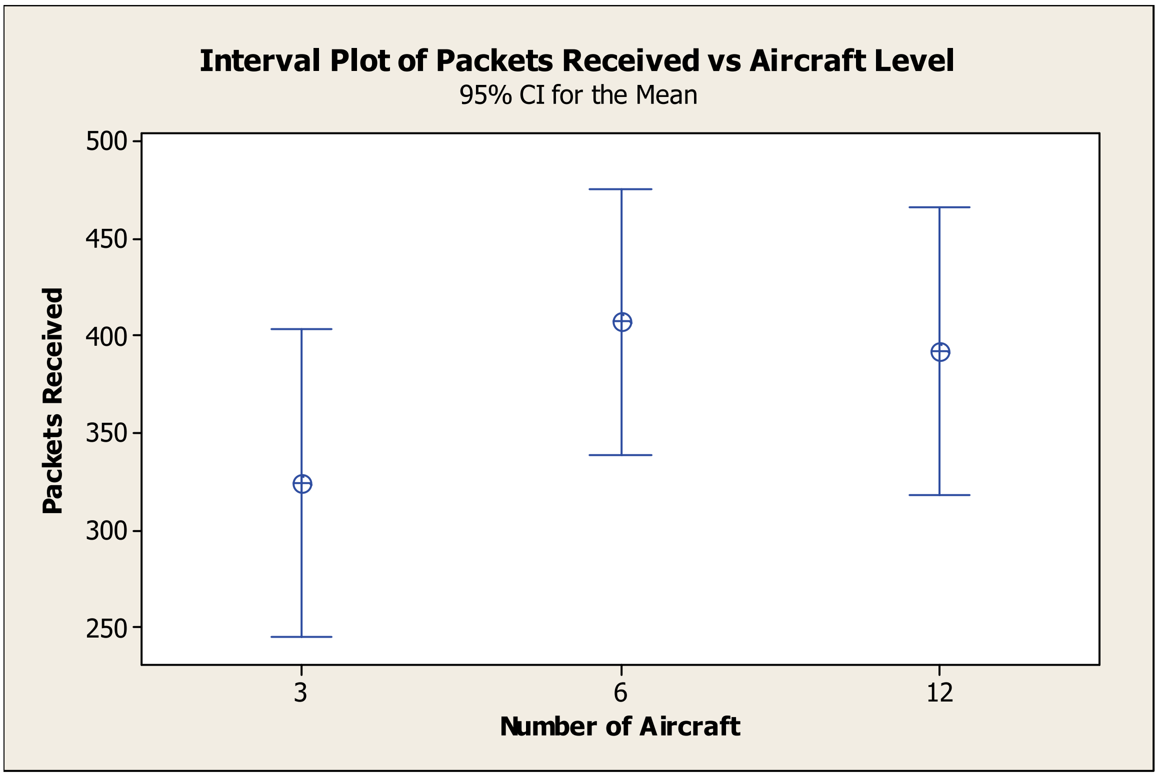

Figure 26. Interval plot of number of packets received versus number of aircraft

Figure 27 is an interval plot of the number of packets received versus the level of background traffic. This plot shows the 95% confidence interval centered about the mean for each level of background traffic. Table 20 lists the background traffic levels, their means, and the ranges of the 95% confidence interval. Because the confidence intervals do not overlap between the 2 levels, it is clear to see that the addition of 1 Mbps background traffic impacts the number of packets received at the destination.

Table 20. Packets received vs background traffic 95% confidence intervals

Background Traffic Levels	Mean	95% Confidence Interval
None	586.55	532.918 – 640.182
1 Mbps	214.642	173.784 – 255.5

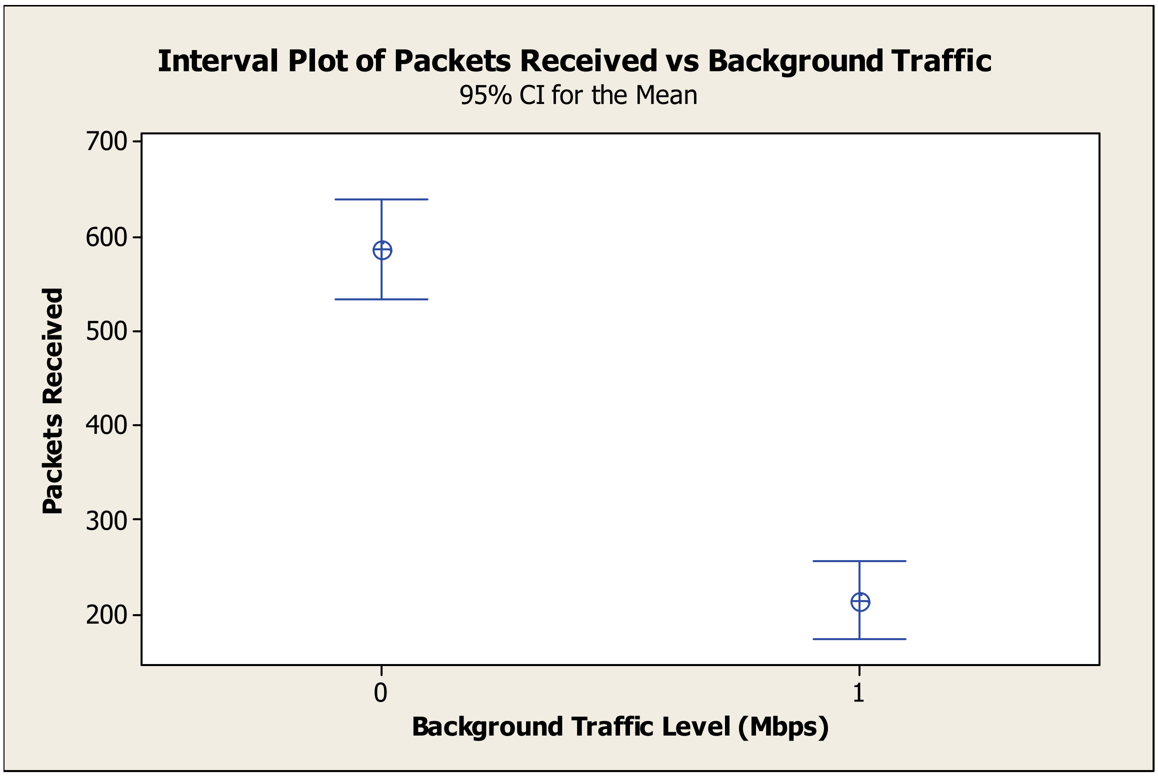

Figure 27. Interval plot of packets received versus level of background traffic

4.4.3 Analysis of Throughput

The general linear model is used to perform the analysis of variance (ANOVA). The ANOVA model is set up with the throughput as the response, where protocol, aircraft levels, and background traffic level as are identified as the predictors, along with their two and three-way interactions. Results of the ANOVA are shown in Table 21.

The introduction of background traffic generates the highest level of throughput variance with 30.21% across 1 degree of freedom. Protocol choice also has a large impact on throughput with a variance of 36.17% across 3 degrees of freedom. The two-way interaction between the addition of background traffic and the choice of protocol generates a very small variance of 4.37% across 3 degrees of freedom. While random error shows an impact on throughput (17.45% variance), this is spread across 151 degrees of freedom, making the error for each degree of freedom very small. The variance generated by the number of aircraft (1.45% across 2 degrees of freedom), the two-way interaction between protocol choice and number of aircraft (2.10% across 6 degrees of freedom), the two-way level interaction between number of aircraft and background traffic (0.06% across 2 degrees of freedom), and the three-way interaction between protocol choice, number of aircraft, and background traffic (0.24% across 6 degrees of freedom) are all small enough to be negligible.

Table 21. ANOVA results for throughput

Source	**DF**	**Seq SS**	**% Variance**
Protocol	3	99,812,923,117	36.1691%
Number of Aircraft	2	4,009,335,828	1.4529%
Background Traffic	1	83,357,333,264	30.2061%
Protocol*Number of Aircraft	6	5,779,662,269	2.0944%
Protocol*Background Traffic	3	12,065,626,249	4.3722%
Number of Aircraft* Background Traffic	2	161,280,317	0.0584%
Protocol*Number of Aircraft* Background Traffic	6	672,770,739	0.2438%
Error	151	70,102,677,928	25.403%
Total	174	$2.75962 * 10^{11}$	

Figure 28 is an interval plot of the throughput versus the routing protocol. This plot shows the 95% confidence interval centered about the mean for each routing protocol. Table 22 lists the protocols, their means, and the ranges of the 95% confidence interval. AODV and DYMO perform better than Fisheye and ZRP. However, because AODV and DYMO have overlapping confidence intervals without the mean of either

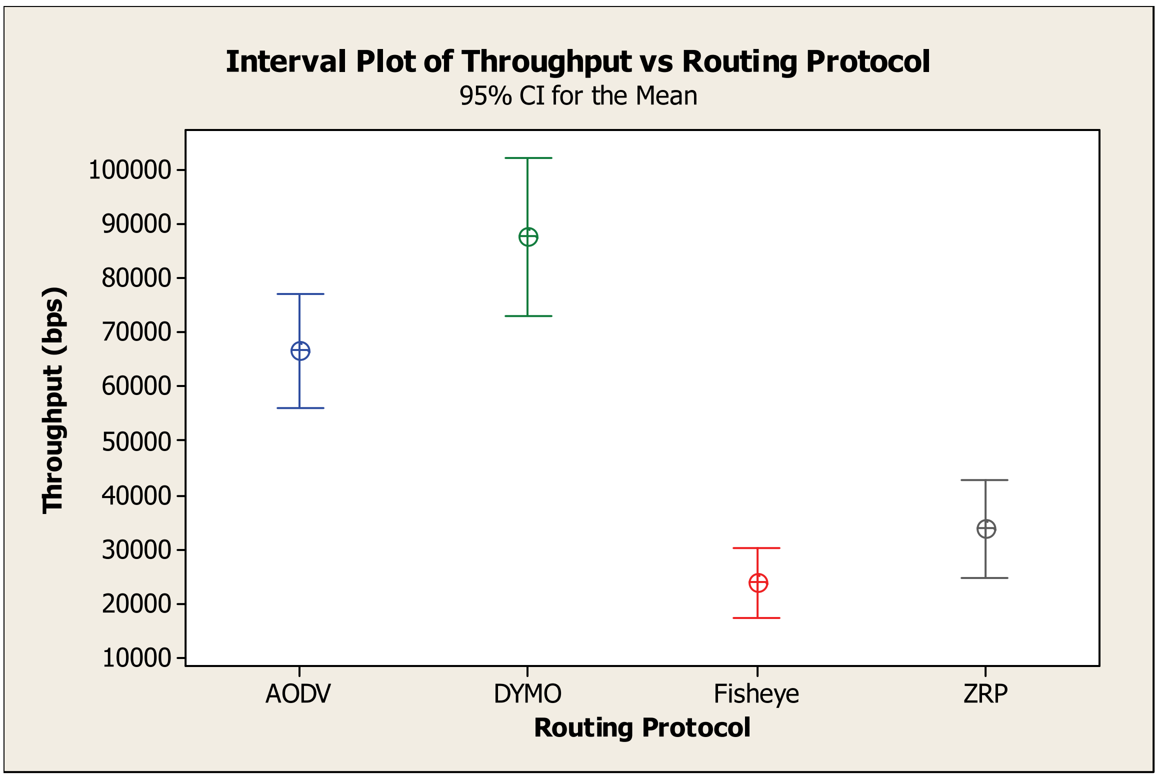

Figure 28. Interval plot of throughput versus routing protocol

falling in the confidence interval of the other, and the same occurs between Fisheye and ZRP, t-tests are used to indicate which routing protocol is the better performer between the two overlapping pairs.

Results of the t-test for AODV and DYMO generate a confidence interval of

[-38,781.6, -3,372.16]. Because this confidence interval does not contain 0, the performance between AODV and DYMO is significantly different. Results of the t-test for Fisheye and ZRP generate a confidence interval of [-21,024.6, 965.848]. Because this confidence interval contains 0, Fisheye and ZRP performance is not significantly different.

Table 22. Throughput vs routing protocol 95% confidence intervals

Routing Protocol	Mean (bps)	95% Confidence Interval
AODV	66,500.5	55,907.5 – 77,093.6
DYMO	87,577.4	72,985.4 – 102,169
Fisheye	23,630.4	17,255.9 – 30,004.9
ZRP	33,659.8	24,556.4 – 42,763.1

Figure 29 is an interval plot of the throughput versus the number of aircraft. This plot shows the 95% confidence interval centered about the mean for each level of aircraft. Table 23 lists the aircraft levels, their means, and the ranges of the 95% confidence interval. The 6-aircraft and 12-aircraft confidence intervals overlap with the means falling within the confidence interval. The same can be observed between the 3-aircraft and 12-aircraft confidence intervals. This indicates no significant difference between these two sets of comparisons. However, the confidence intervals of the 3 and 6-aircraft levels overlap without the means falling within these intervals. A t-test is performed to compare this significance. Results of the t-test for 3 and 6-aircraft levels generate a confidence interval of [-26,215.4, 3,881.4]. Because this confidence interval contains 0, the performance between the 3 and 6-aircraft levels is not significantly different.

Table 23. Throughput vs number of aircraft 95% confidence intervals

Number of Aircraft	Mean (bps)	95% Confidence Interval
3	41,540.8	29,897.8 – 53,183.8
6	52,708	42,853.5 – 62,562.5
12	48,675.2	38,893.1 – 58,457.3

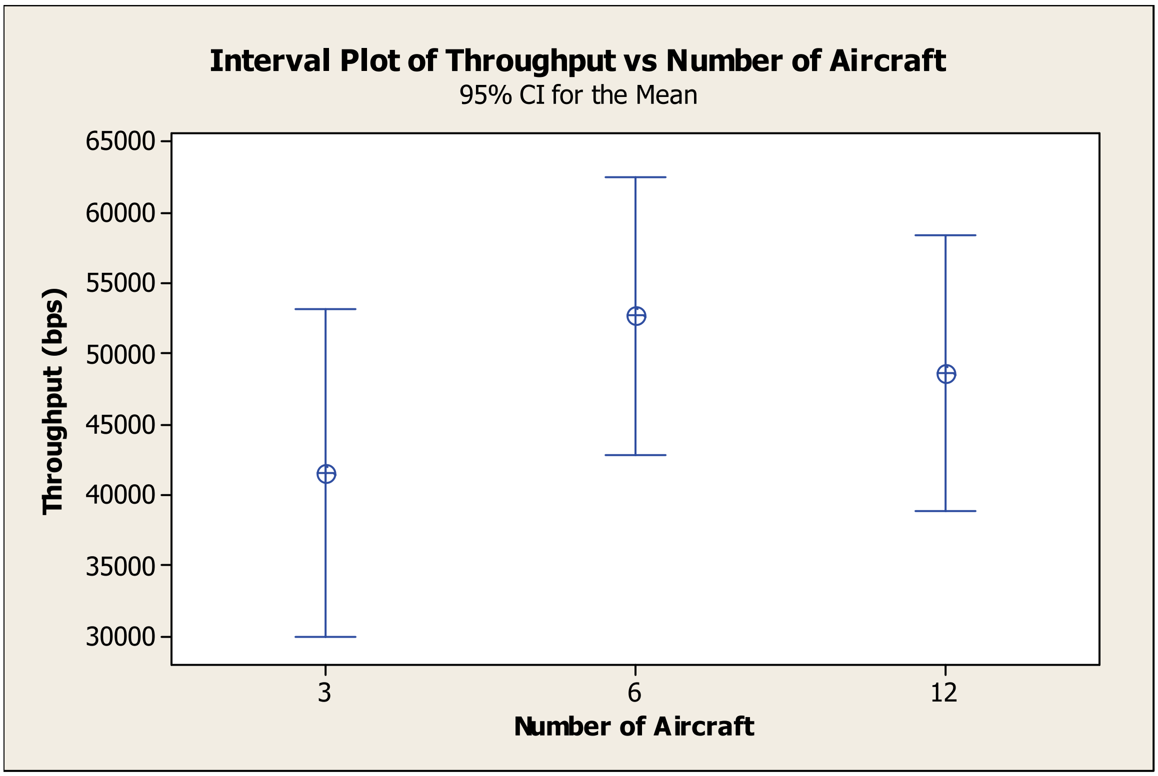

Figure 29. Interval plot of throughput versus number of aircraft

Figure 30 is an interval plot of the throughput versus the level of background traffic. This plot shows the 95% confidence interval centered about the mean for each level of background traffic. Table 24 lists the background traffic levels, their means, and the ranges of the 95% confidence interval. Because the confidence intervals do not overlap between the 2 levels, it is clear to see that the addition of 1 Mbps background traffic impacts the number of packets received at the destination.

Table 24. Throughput vs background traffic 95% confidence intervals

Background Traffic Levels	Mean (bps)	95% Confidence Interval
None	75,312.2	67,244.4 – 83,380.0
1 Mbps	26,587.1	21,066.8 – 32,107.4

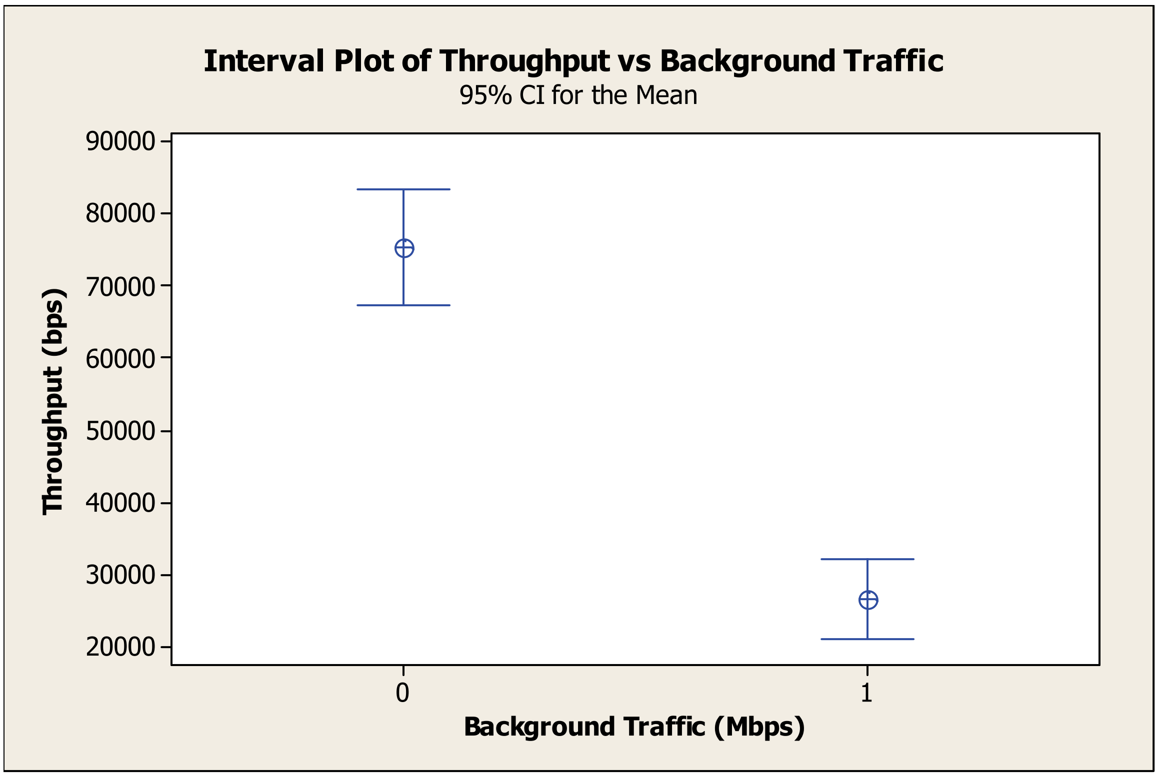

Figure 30. Interval plot of throughput versus level of background traffic

4.5 Summary of Analysis and Results

Choice of routing protocol does cause variance in the performance of the average ETE delay, number of packets received, and throughput. The choice of routing protocol shows more impact (across 3 degrees of freedom) on number of packets received (41.4%) and throughput (36.2%), but still has a large impact on average ETE delay (20.0%). This analysis is important in understanding the role that selection of routing protocol does play in MANET performance.

Using confidence interval analysis, AODV performed at a high rate across each metric. DYMO performance was very similar to that of AODV, but problems in performance were observed in the simulator with background traffic added to the MANET. ZRP and Fisheye performed similarly compared to each other, but fell short of the performance results observed by the two reactive protocols. Table 25 provides a summary of how each protocol performed ranked against the others for each performance metric. Two protocols listed within the same ranking indicate that there was no significant difference in performance between the two in the given metric.

Table 25. Ranking protocol performance

Rank	Average ETE Delay	Number of Packets Received	Throughput
1	AODV	AODV, DYMO	DYMO
2	DYMO		AODV
3	Fisheye, ZRP	ZRP	Fisheye, ZRP
4		Fisheye	

This chapter has covered the results and analysis of this study. Validation of the data collected was first presented. An explanation of how QualNet statistics are calculated was then presented to identify the independent nature of the metrics collected. Next, ZRP and DYMO discrepancies were addressed. ANOVA results and analysis were then presented about the performance metrics and the impact of each factor on those metrics, followed by results and analysis on the routing protocol performance. Recommendations and conclusions are presented in the following chapter.

V. Conclusions and Recommendations

This chapter concludes the documentation of the research performed. Section 5.1 presents a summary of the conclusions drawn from the analysis and results. Section 5.2 discusses the significance of this research. Section 5.3 discusses recommendations for further research, and Section 5.4 briefly summarizes this chapter.

5.1 Conclusions of Research

Several conclusions can be drawn from the results and analysis of this research.

1) Reactive routing demonstrated better overall performance than hybrid and proactive routing. AODV, along with DYMO, showed lower average ETE delays and higher packets received and throughput than those observed with Fisheye and ZRP. This conclusion is not surprising given the small number of nodes and high mobility of the network.

2) ZRP and Fisheye average ETE delay and throughput performance shows no significant difference. However, in number of packets received performance, ZRP outperforms Fisheye. Given the small number of nodes in the network and the physical size and transmission constraints of this network, the hybrid routing protocol does route with its proactive component a majority of the time. The MANETs modeled in this study are not suitable to benefit from the advantages offered by the hybrid routing protocol.

3) The physical constraints of the network configurations (the region size, the communication ranges, the number of mobile nodes, and the random mobility patterns of the mobile nodes) impacts routing performance. When the number of aircraft nodes is equivalent to the minimum required hops for data transmission, the random mobility of

the aircraft make it extremely difficult to transmit data. This is observed in the results from the 3-aircraft configuration with no background traffic.

5.2 Significance of Research

This research benefits AFCA's development of a standard framework for an ad hoc airborne network. By observing and comparing routing protocol performance in a modeled environment under AFCA-guided physical restraints, this study offers initial recommendations on routing protocol selection and provides direction for further research into this area.

5.3 Recommendations for Future Research

Further research into the development of a standard framework for an ad hoc airborne network must be performed before any definitive conclusions can be drawn.

Because AFCA primarily works with OPNET, proposals for furthering their research include:

- Using the QualNet model used in this study, build the same network model in OPNET and compare routing performance using those protocols common in both simulators (i.e. AODV). This comparison would provide a good indication of how useful this research is to their organization, and would help them determine if QualNet is a network simulator they want to continue to invest in.

- The implementation issues with DYMO need to be presented to and addressed by QualNet.

- The QualNet implementation of ZRP needs to be further understood. Observing the same results using two separate radii indicates that ZRP has implementation problems.

The benefit of this research to AFCA depends heavily on the confidence in the QualNet simulator.

Many of the physical parameters chosen in this study, if modified, may provide different results. The modification of the following parameters may impact routing protocol performance: aircraft characteristics (altitude and speed), radio characteristics (choice of radio and propagation patterns), mobility patterns, number of nodes within the network, and the level of background traffic in this system. The modification of each of these parameters provides research opportunities. Within the OSI protocol stack, further opportunities for research exist in the physical and data link layers.

Fisheye and ZRP routing can be further studied with changes to scope and zone radius. With a radius of 1, ZRP operates solely with its reactive component. ZRP performance in this research may have been better if the zone radius was set to 1. Along the same vein, other routing protocols may provide more capable routing solutions than those studied in this paper.

Further research exists with the selection of network simulation tool. Network performance may yield differing results if tested on other simulators, including OPNET, ns2, and Glomosim. Further study into this would provide interesting results.

5.4 Summary

This chapter presents the overall conclusions that are drawn from the results. Research significance was discussed. And, several recommendations and avenues for future research are offered.

Appendix A – Supporting Data

This appendix provides data to support the analysis of this study. This appendix is divided into multiple sections. Section A.1 discusses the MANET configuration models used in this study. Section A.2 presents the data gathered in this study and discusses the routing protocol performance metrics.

A.1 MANET Configuration Models

Six MANET configurations are modeled in this study, identified in Table 6 in Section 4.3. The configurations with 3 aircraft are shown in Figures 20 and 21 of the same section. The configurations with 6 aircraft are shown in Figures 17 and 18 of Section 3.9. Figures A1 and A2 show the 12-aircraft configurations used in this study.

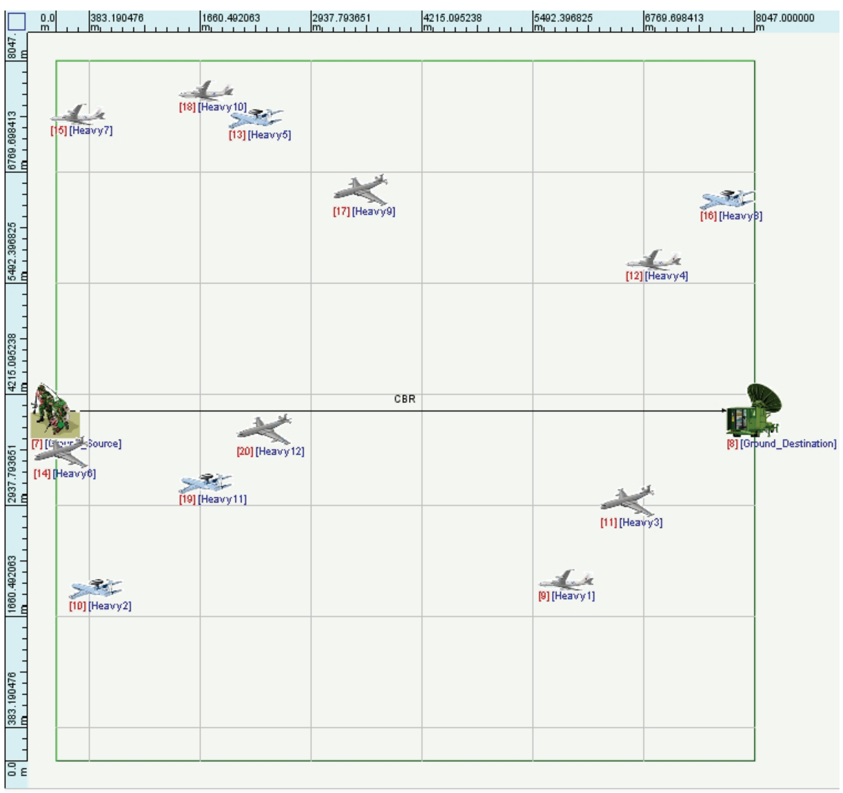

Figure A1. MANET with 12 aircraft nodes (no background traffic)

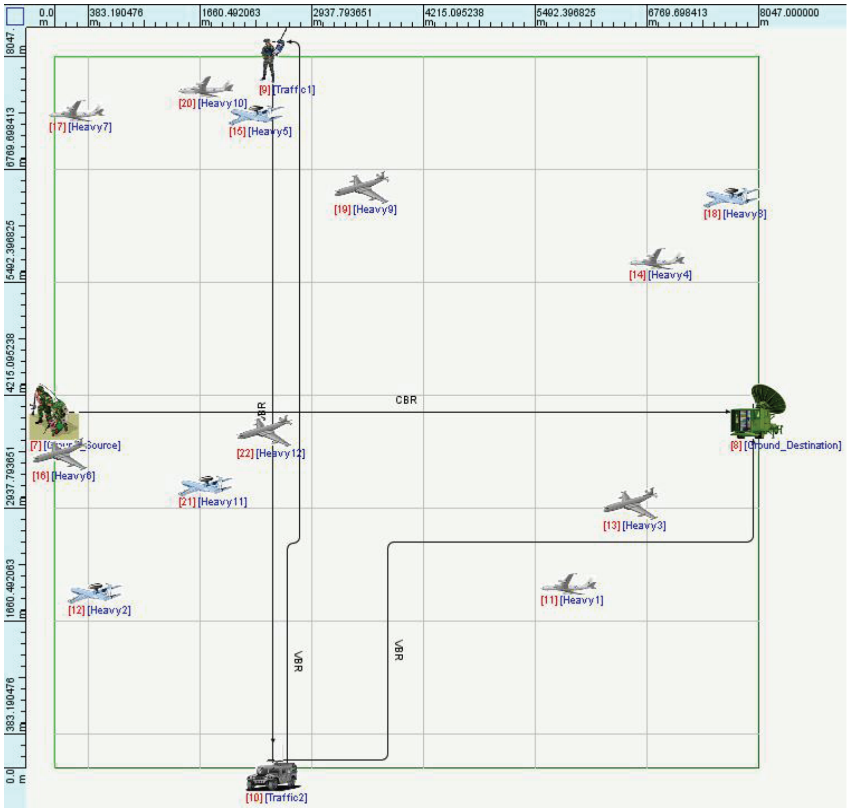

Figure A2. MANET with 12 aircraft nodes (background traffic included)

A.2 Performance Metric Data

This section presents the raw data observed for average ETE delay, number of packets received, and throughput. Data from the 3-aircraft configuration with no additional background traffic is excluded from the data analysis, per discussion in Section 4.3.1, but is presented here. Packets received and throughput data from this configuration are presented in Section 4.3.1 and not shown in this section.

A.2.1 Average ETE Delay

Table A1 lists the routing protocol average ETE delay data collected for each experiment run using the 3-aircraft configuration with no background traffic. A '--' in the table indicates that the destination received no data throughout the course of the experiment.

Table A1. Average ETE delay (s) for 3-aircraft MANET (no background traffic)

AODV	DYMO	Fisheye	ZRP
0.806735554	0.810651303	--	0.790674695
0.779855711	0.800951673	--	0.822072554
0.908286515	0.813151914	0.799888301	0.790190075
0.815592495	0.783116615	0.800160515	--
0.841868124	0.818330279	0.804578902	0.798941082
0.804378913	--	0.749439084	--
0.791550499	--	--	0.791575634
0.807484045	0.84890069	0.819349165	0.828642323
0.814423136	0.805461917	0.767189225	--
0.81117983	0.820731988	0.785688747	0.775166829

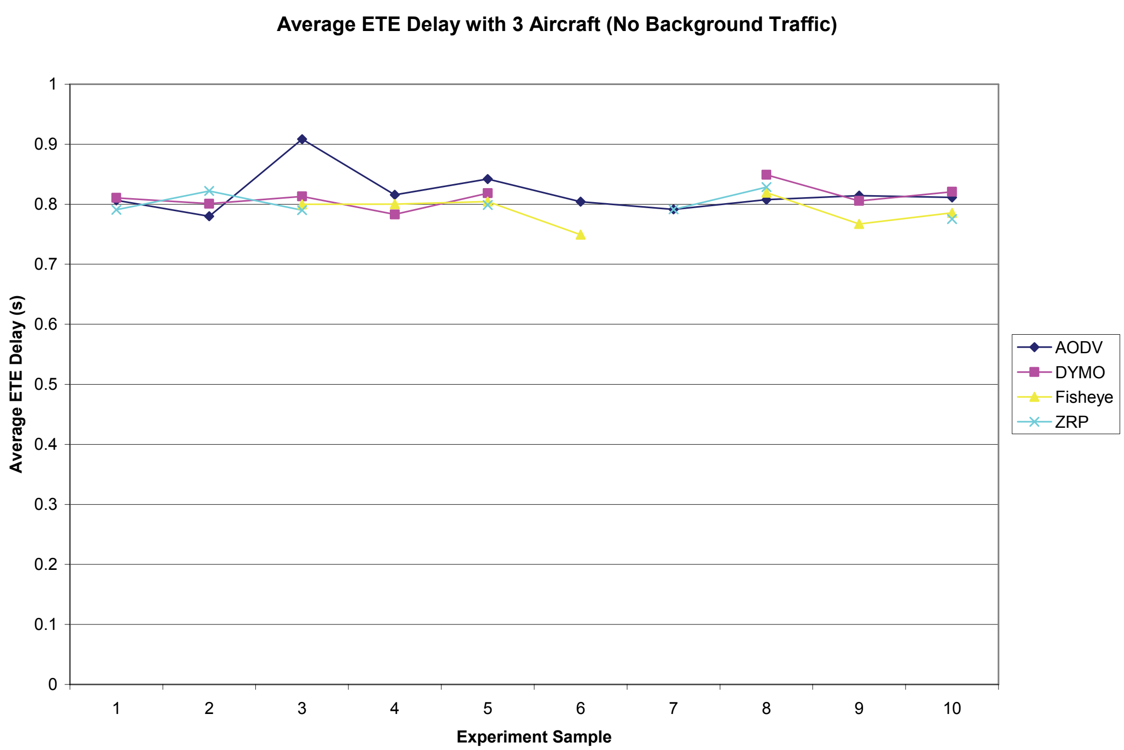

Figure A3. Average ETE delay for 3-aircraft MANET (no background traffic)

The average ETE delays observed in this 3-aircraft MANET are graphed in Figure A3. Using only recorded data, average ETE delay mean values are:

AODV	0.8181 secs
DYMO	0.8127 secs
Fisheye	0.7895 secs
ZRP	0.7996 secs

Under this configuration, average ETE delay is observed to be similar across the samples.

Table A2 lists the routing protocol average ETE delay data collected for each experiment run using the 3-aircraft configuration with additional background traffic placed on the system.

Table A2. Average ETE delay (s) for 3-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
1.678288556	--	0.793856691	26.94670556
1.147787756	5.802667109	196.6433952	297.8980399
1.048634725	2.670704564	26.06176857	211.0061486
1.806821986	1.10849744	--	45.5434294
0.853609865	1.091025853	0.884438262	24.30326827
1.315223811	--	0.789028382	45.38958651
0.928297149	1.847961957	62.50647029	153.7799326
1.150888401	2.711382048	23.75446171	257.4776279
2.115599563	--	165.1177599	337.2210057
1.264568523	--	135.8794537	134.2101504

The average ETE delays observed in this 3-aircraft MANET are plotted in Figure A4. Using only recorded data, average ETE delay mean values are:

AODV	1.331 secs
DYMO	2.539 secs
Fisheye	68.05 secs
ZRP	153.4 secs

As shown in the figure, AODV samples show the lowest average ETE delays. DYMO samples show a greater delay, and Fisheye and ZRP show drastically greater delays.

Table A3 lists the routing protocol average ETE delay data collected for each experiment run using the 6-aircraft configuration with no background traffic.

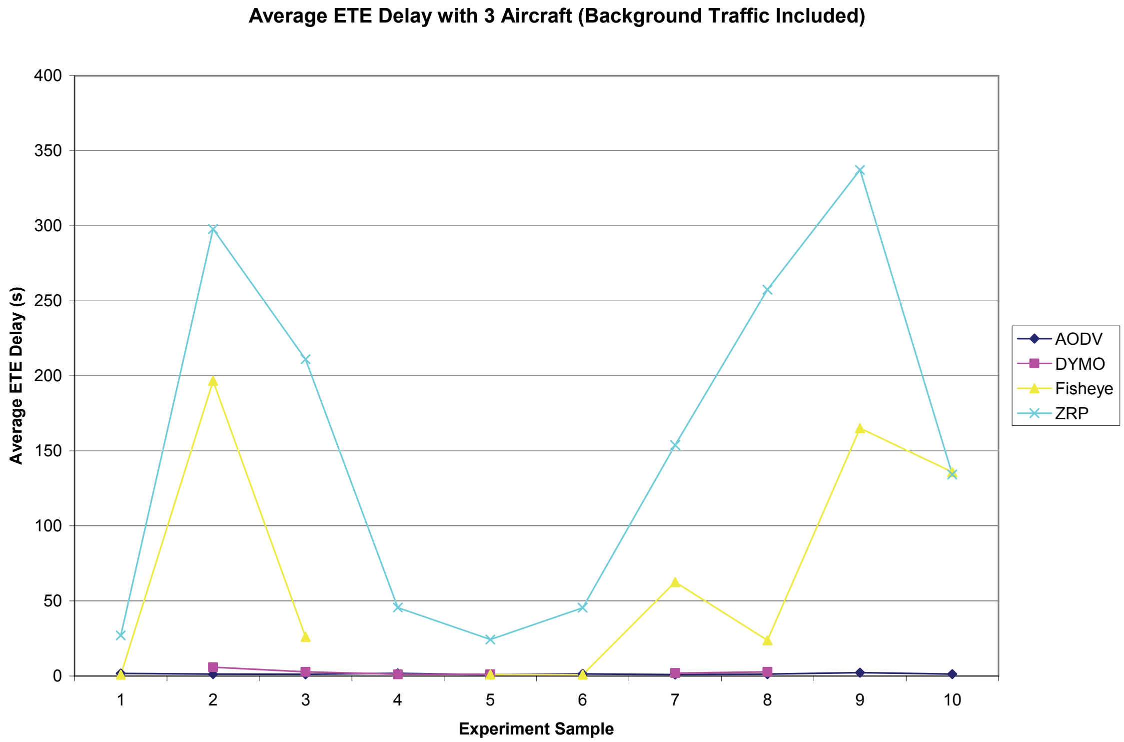

Figure A4. Average ETE delay for 3-aircraft MANET with background traffic

Table A3. Average ETE delay (s) for 6-aircraft MANET (no background traffic)

AODV	DYMO	Fisheye	ZRP
0.850298768	1.129925241	0.790688611	0.798667169
0.842785795	1.398857334	0.957178765	10.25200397
0.869085711	1.551527626	1.05454684	30.37283397
0.860289576	1.167188916	0.789103956	0.797258505
0.843994741	1.030026133	0.808761579	29.18149224
0.838481036	1.158702387	4.229161168	7.18004361
0.862389321	1.366656815	0.844237778	64.89174382
0.842635333	1.252573995	0.78953279	24.13833935
0.842813704	1.391039892	0.789100804	5.328445354
0.868789773	1.363512091	1.579249103	1.485056158

The average ETE delays observed in this 6-aircraft MANET are plotted in Figure A5. Average ETE delay mean values are:

AODV	0.8522 secs
DYMO	1.281 secs
Fisheye	1.263 secs
ZRP	17.44 secs

Using mean values, compared to the delays observed in the 3-aircraft configuration with no offered load, the average ETE delay increases by the following percentage (impact of increased aircraft nodes):

AODV	4.2% increased delay
DYMO	57.6% increased delay
Fisheye	60.0% increased delay
ZRP	2,081.1% increased delay

As shown in the data, AODV and DYMO show a more consistent average ETE delay across the samples than do Fisheye and ZRP. Looking at the figure, ZRP results are very

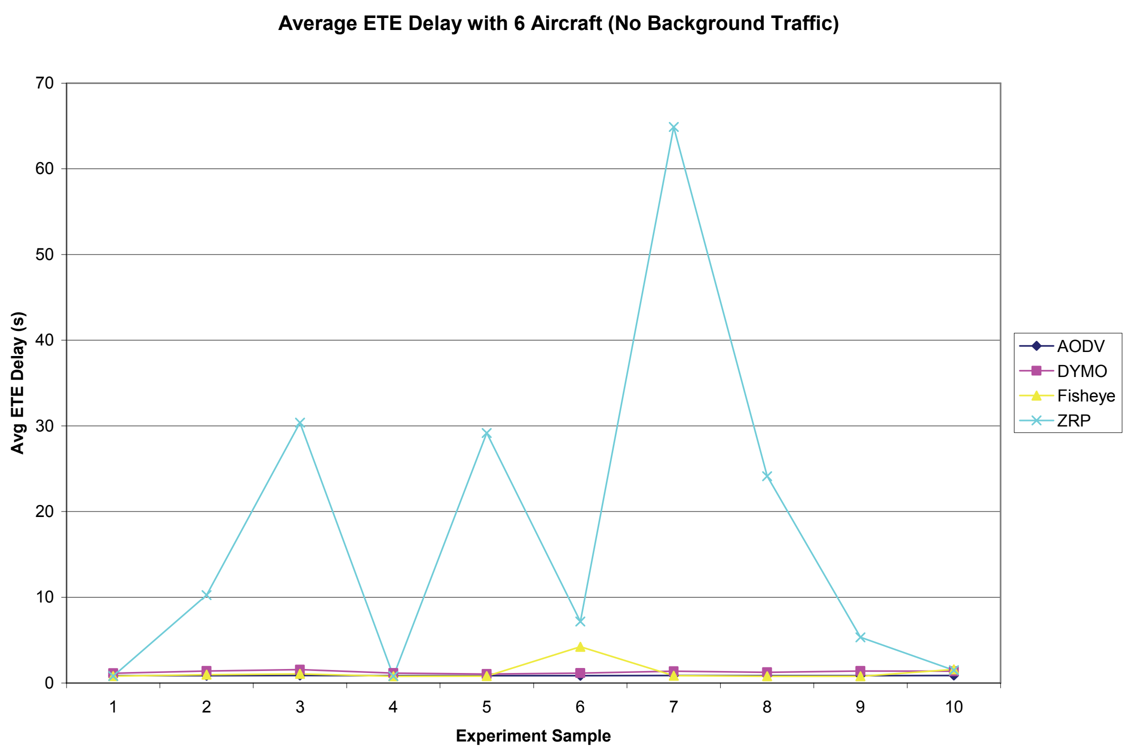

Figure A5. Average ETE delay for 6-aircraft MANET (no background traffic) inconsistent ranging from under 1 second to over 64 seconds.

Table A4 lists the routing protocol average ETE delay data collected for each experiment run using the 6-aircraft configuration with additional background traffic placed on the system. DYMO discrepancies are discussed in Section 4.2.

Table A4. Average ETE delay (s) for 6-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
1.343067506	--	460.1221769	67.85829819
1.426614769	--	480.2245502	402.1522262
1.137989159	--	311.2507085	451.7757094
1.88372308	--	91.94605074	107.4851635
1.120212475	--	290.700247	170.1811919
1.312020528	--	475.3322004	167.8234935
1.409837238	--	184.212752	810.3637306
1.332618867	--	193.1838101	186.2379446
2.021186579	--	767.1401925	843.5696233
1.255120215	--	501.0859423	750.366812

The average ETE delays observed in this 6-aircraft MANET are plotted in Figure A6. Average ETE delay mean values are:

AODV	1.424 secs
Fisheye	375.5 secs
ZRP	395.8 secs

Using mean values, compared to the delays observed in the 3-aircraft configuration with additional background traffic, the average ETE delay increases by the following percentage (impact of increased aircraft nodes):

AODV	7.0% increased delay
Fisheye	451.8% increased delay
ZRP	158.0% increased delay

Using mean values, compared to the delays observed in the 6-aircraft configuration with no background traffic, the average ETE delay increases by the following percentage (impact of additional load):

AODV	67.1% increased delay
Fisheye	29,630.8% increased delay
ZRP	2,169.5% increased delay

Adding the background traffic to the system has a greater impact on average ETE delay than the impact caused by increasing the number of aircraft nodes from 3 to 6. While each protocol shows increased average ETE delay times, the reactive routing protocol samples show the smallest increase, followed by the hybrid protocol, with the proactive routing protocol ETE delay samples increasing much higher as the number of

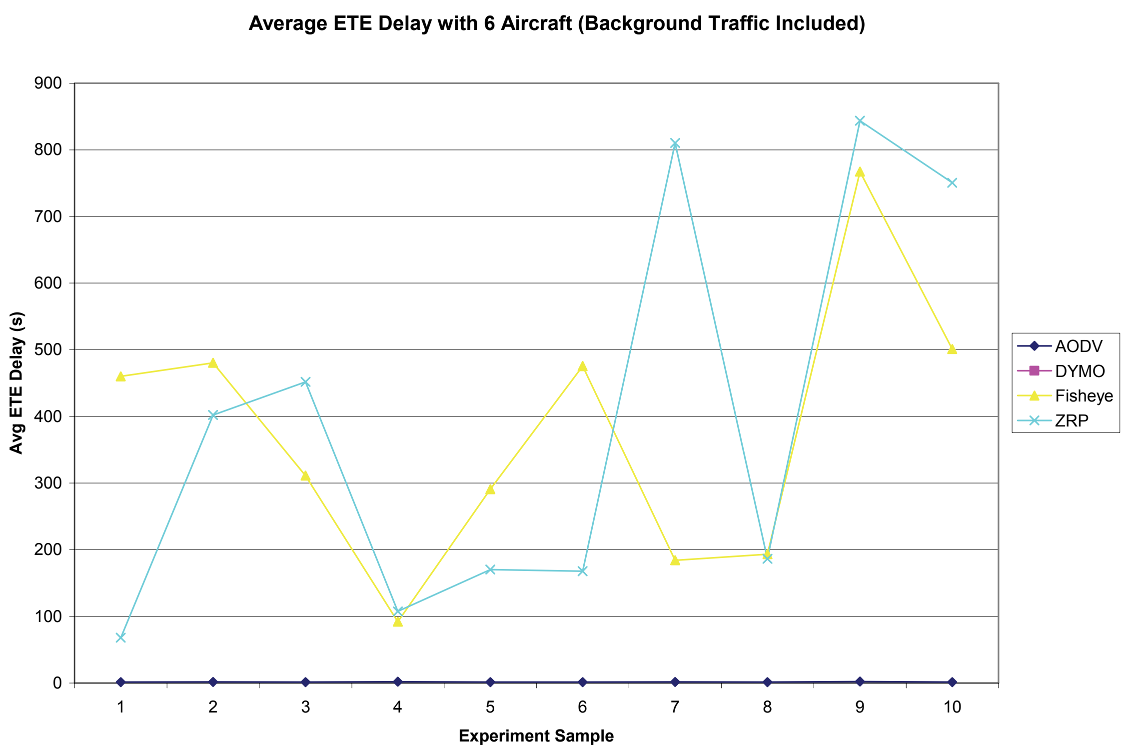

Figure A6. Average ETE delay for 6-aircraft MANET with background traffic nodes are increased and with the addition of the offered load.

AODV shows a more consistent and smaller average ETE delay across the samples than do Fisheye and ZRP. Fisheye and ZRP results are very inconsistent across the samples and produce very large ETE delays.

Table A5 lists the routing protocol average ETE delay data collected for each experiment run using the 12-aircraft configuration with no background traffic.

The average ETE delays observed in this 12-aircraft MANET are plotted in Figure A7. Average ETE delay mean values are:

AODV	0.9113 secs
DYMO	1.314 secs
Fisheye	3.085 secs
ZRP	28.95 secs

Using mean values, compared to the delays observed in the 6-aircraft configuration with no background traffic, the average ETE delay increases by the following percentage (impact of increased aircraft nodes):

AODV	6.9% increased delay
DYMO	2.6% increased delay
Fisheye	144.3% increased delay
ZRP	66.0% increased delay

Table A5. Average ETE delay (s) for 12-aircraft MANET with no background traffic

AODV	DYMO	Fisheye	ZRP
0.906868464	1.254897932	0.799067745	26.10536665
0.929799574	1.384650335	6.651126546	18.87963121
0.918290572	1.33754426	0.997015839	16.78128174
0.929903369	1.31073945	0.795027118	122.7653151
0.887220503	1.103792685	0.808260338	11.08343396
0.926910109	1.361543917	1.462459788	26.50534279
0.896473181	1.456858255	8.116689714	20.57775192
0.919133425	1.400794806	5.271272599	4.030413247
0.880789587	1.24886453	0.847305857	18.62729825
0.917884899	1.280102889	5.104776776	24.15526266

The impact of increasing the number of aircraft from 6 to 12 under this configuration has the greatest impact on Fisheye and ZRP.

AODV and DYMO show a more consistent average ETE delay across the samples than do Fisheye and ZRP. ZRP results are very inconsistent ranging from 4 seconds to over 122 seconds across the samples.

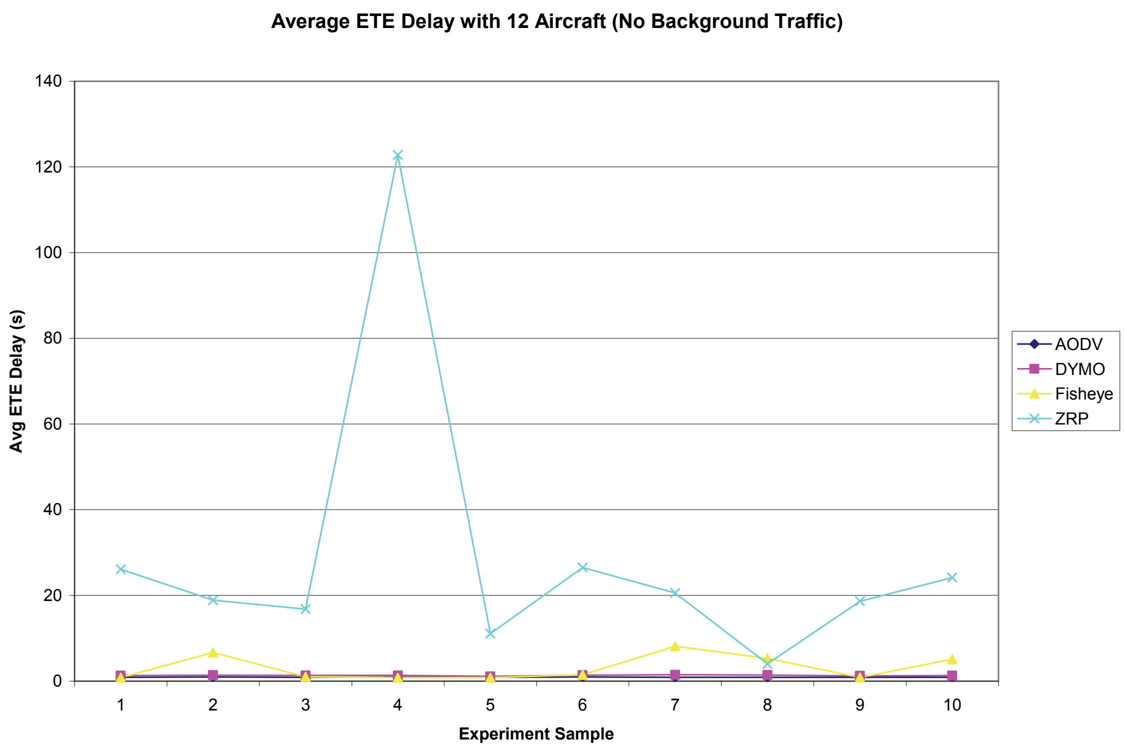

Figure A7. Average ETE delay for 12-aircraft MANET (no background traffic)

Table A6 lists the routing protocol average ETE delay data collected for each experiment run using the 12-aircraft configuration with additional background traffic placed on the system. DYMO discrepancies are discussed in Section 4.2.

Table A6. Average ETE delay (s) for 12-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
1.233274837	--	62.13036616	--
1.560320374	9.684450119	662.7911832	--
1.121495691	--	667.7766502	570.4301843
1.4778924	--	147.3888894	1312.972924
1.104789547	--	303.3462748	474.4150694
1.364621619	--	517.0627327	70.24769649
1.335915522	--	367.0575765	358.5033432
1.372484495	--	226.2410807	233.2149059
1.413946969	--	512.8516749	492.6758264
1.480281057	9.133166489	438.5780503	223.5920697

The average ETE delays observed in this 12-aircraft MANET are plotted in Figure A8. Using only recorded data, average ETE delay mean values are:

AODV	1.347 secs
DYMO	9.409 secs
Fisheye	390.5 secs
ZRP	467.0 secs

Using mean values, compared to the delays observed in the 6-aircraft configuration with an offered load, the average ETE delay changes by the following percentage (impact of increased aircraft nodes):

AODV	5.4% decreased delay
Fisheye	4.0% increased delay
ZRP	18.0% increased delay

Using mean values, compared to the delays observed in the 12-aircraft configuration with no offered load, the average ETE delay increases by the following percentage (impact of additional load):

AODV	47.8% increased delay
Fisheye	12,558.0% increased delay
ZRP	1,513.1% increased delay

Adding the offered load to the system has a far greater impact on average ETE delay across the samples than the impact caused by increasing the number of aircraft nodes from 6 to 12. By increasing the number of aircraft, AODV average ETE delay samples decreased. Fisheye samples showed only a minimal increase in delay, while ZRP showed a larger increase in delay with the increase in aircraft.

As observed in the 6-aircraft configuration, when background traffic is added to the system, average ETE delays increase dramatically. AODV is by far the best performer in managing routing with this additional traffic.

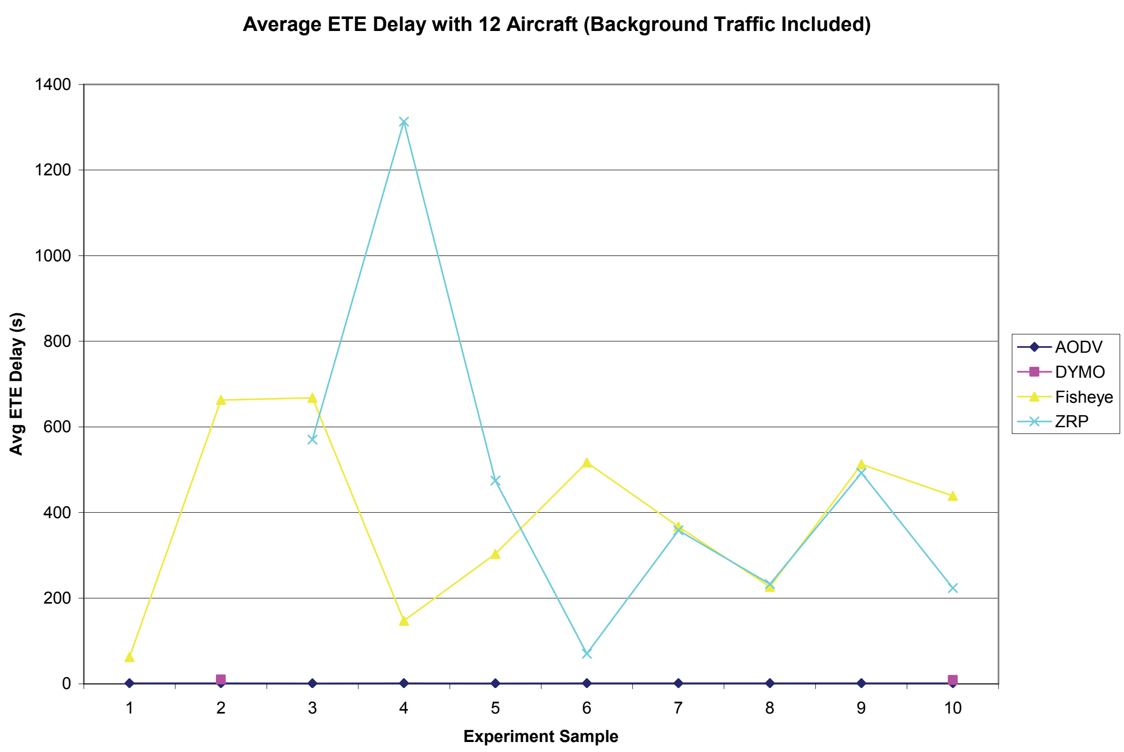

Figure A8. Average ETE delay for 12-aircraft MANET with background traffic

AODV shows a more consistent and smaller average ETE delay across the samples than do Fisheye and ZRP. Fisheye and ZRP results are very inconsistent across the samples and produce very large ETE delays.

A.2.2 Number of Packets Received

The number of packets received data for the 3-aircraft configuration with no background traffic is addressed in Section 4.3.1.

The number of packets received at the destination using the 3-aircraft configuration with additional background traffic is shown in Table A7 and plotted in Figure A9. Using only recorded data, mean values for packets received are:

AODV	413.5 packets
DYMO	530.3 packets
Fisheye	194.2 packets
ZRP	227.6 packets

As shown in Figure A9, DYMO and AODV samples show similar results, as do the Fisheye and ZRP samples. AODV and DYMO provide higher packets received results than Fisheye and ZRP.

Table A7. Packets received for 3-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
156	--	72	90
545	559	129	218
581	552	213	298
205	226	--	76
729	687	330	417
221	--	26	55
724	781	637	647
417	377	122	148
147	--	99	190
410	--	120	137

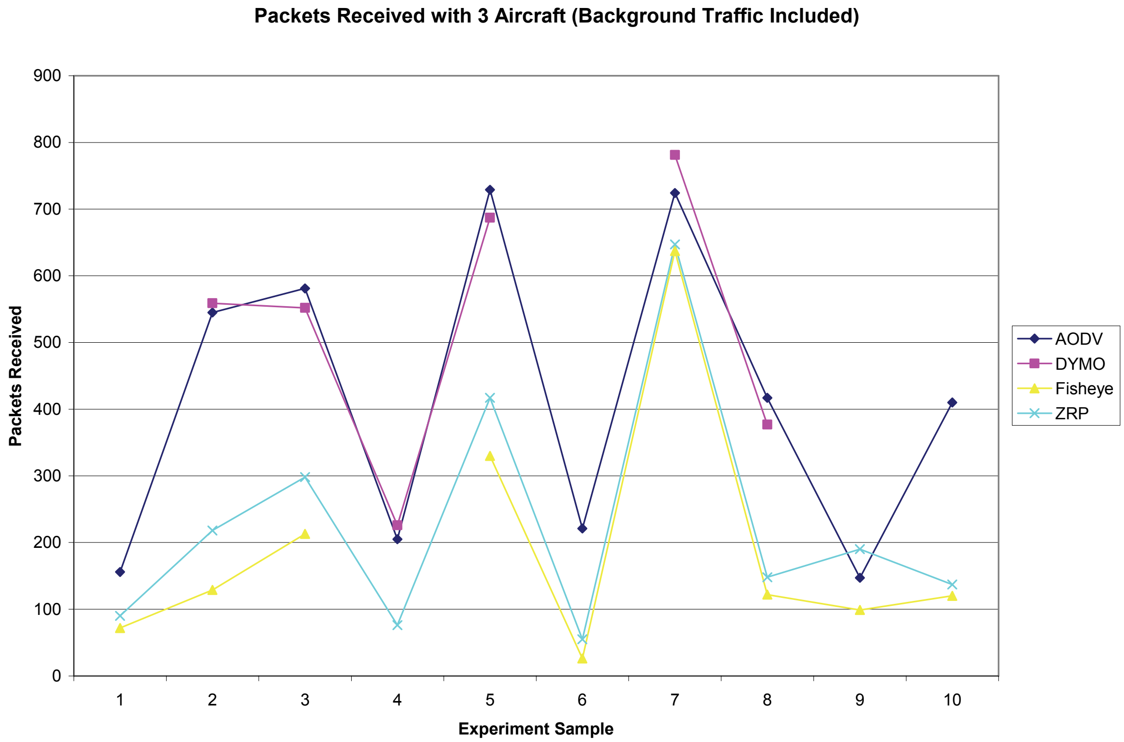

Figure A9. Packets received for 3-aircraft MANET with background traffic

The number of packets received at the destination using this configuration are shown in Table A8 and plotted in Figure A10. Mean values for packets received are:

AODV	772.2 packets
DYMO	729.5 packets
Fisheye	336.8 packets
ZRP	526.0 packets

As shown in the Figure A10, DYMO and AODV samples show similar results and see the highest number of packets at the destination. The destination receives the least amount of packets when Fisheye is used. And, ZRP samples fall consistently between the reactive and proactive routing protocol samples.

Table A8. Packets received for 6-aircraft MANET (no background traffic)

AODV	DYMO	Fisheye	ZRP
835	794	446	474
806	782	417	736
833	770	427	618
371	379	202	203
763	749	260	471
665	598	264	283
871	812	276	588
845	820	292	561
855	818	400	638
878	773	384	688

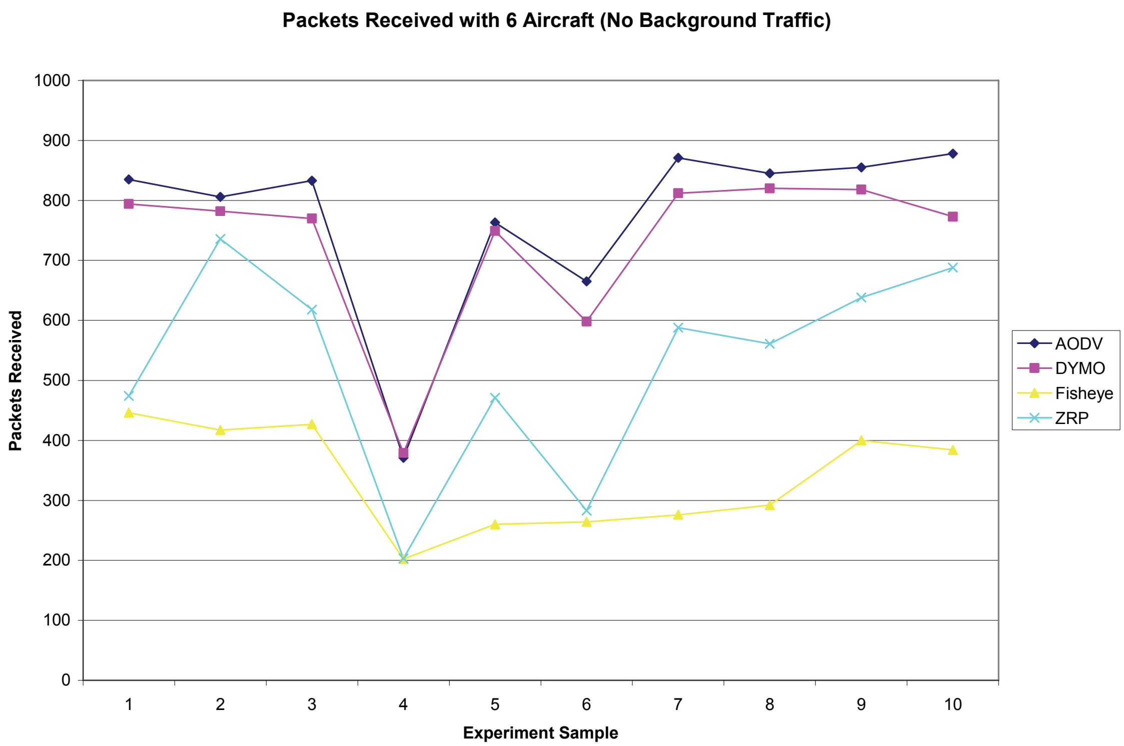

Figure A10. Packets received for 6-aircraft MANET (no background traffic)

The number of packets received at the destination using the 6-aircraft configuration with no background traffic is shown in Table A9 and plotted in Figure A11. Mean values for packets received are:

AODV	323.7 packets
Fisheye	92.5 packets
ZRP	72.2 packets

Using mean values, compared to the packets received observed in the 3-aircraft configuration with background traffic, the number of packets received decreases by the following percentage (impact of increased aircraft nodes):

AODV	21.7% decrease
Fisheye	52.4% decrease
ZRP	68.3% decrease

Using mean values, compared to the packets received observed in the 6-aircraft configuration with no offered load, the number of packets received decreases by the following percentage (impact of additional load):

AODV	58.1% decrease
Fisheye	72.5% decrease
ZRP	86.3% decrease

Adding the background traffic to the system has a greater impact on number of packets received than the impact caused by increasing the number of aircraft nodes from 3 to 6, although this difference in impact is more noticeable with AODV (21.7% versus 58.1%).

Table A9. Packets received for 6-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
203	--	6	8
412	--	145	85
529	--	208	130
177	--	8	21
522	--	91	66
282	--	18	3
437	--	164	198
244	--	34	38
126	--	124	63
305	--	127	110

While each protocol shows a decreased number of packets received, the reactive routing protocol shows the smallest decrease, followed by the proactive protocol, with the hybrid routing protocol showing the highest reduction in packets received.

As shown in Figure A11, AODV results in the highest number of packets received at the destination. The destination receives much fewer packets when Fisheye and ZRP are used.

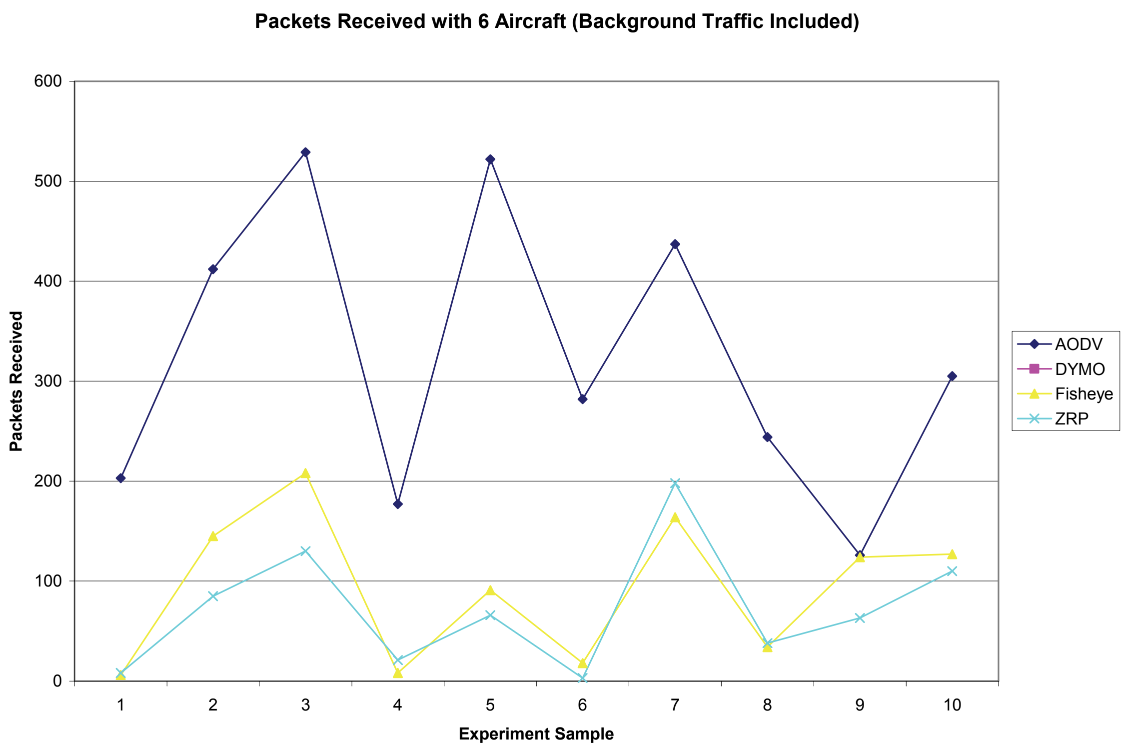

Figure A11. Packets received for 6-aircraft MANET with background traffic

The number of packets received at the destination using the 12-aircraft configuration with no background traffic is shown in Table A10 and plotted in Figure A12. Mean values for packets received are:

AODV	821.1 packets
DYMO	825.1 packets
Fisheye	255.7 packets
ZRP	426.0 packets

Using mean values, compared to the packets received observed in the 6-aircraft configuration with no offered load, the number of packets received changes by the following percentage (impact of increased aircraft nodes):

AODV	6.3% increase
DYMO	13.1% increase
Fisheye	24.1% decrease
ZRP	23.5% decrease

Increasing the number of aircraft nodes from 6 to 12 increases the number of packets received using AODV and DYMO, but decreases the number of packets received using ZRP and Fisheye.

Table A10. Packets received for 12-aircraft MANET (no background traffic)

AODV	DYMO	Fisheye	ZRP
851	797	305	395
851	761	234	454
586	815	336	424
813	828	158	312
864	871	303	478
838	796	195	477
846	841	296	488
867	840	319	583
857	850	251	368
838	852	160	281

As shown in Figure A12, AODV and DYMO samples show the highest number of packets received at the destination. The samples show that the destination receives the fewest number of packets when Fisheye is used, with ZRP results falling in the middle.

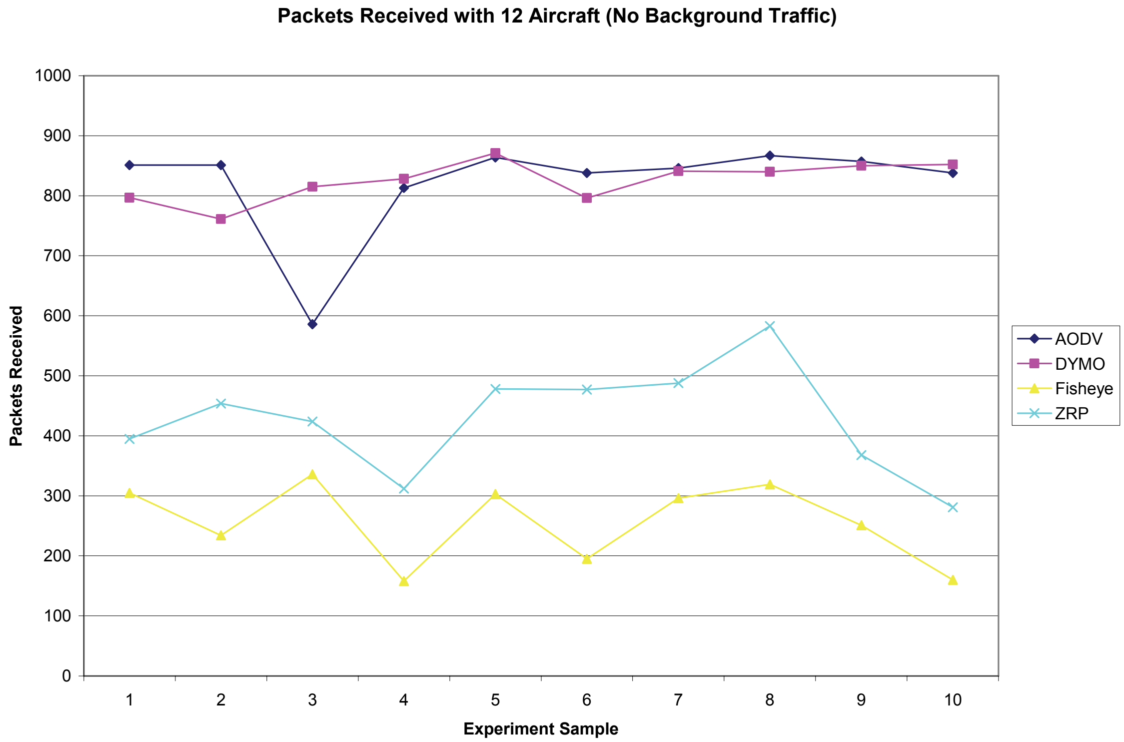

Figure A12. Packets received for 12-aircraft MANET with no background traffic

The number of packets received at the destination using the 12-aircraft configuration with background traffic included is shown in Table A11 and plotted in Figure A13. Using only recorded data, mean values for packets received are:

AODV	327.8 packets
DYMO	19.0 packets
Fisheye	53.5 packets
ZRP	39.4 packets

Using mean values, compared to the packets received observed in the 6-aircraft configuration with background traffic included, the number of packets received changes by the following percentage (impact of increased aircraft nodes):

AODV	1.3% increase
Fisheye	42.2% decrease
ZRP	32.8% decrease

Using mean values, compared to the packets received observed in the 12-aircraft configuration with no background traffic, the number of packets received decreases by the following percentage (impact of additional load):

AODV	60.1% decrease
Fisheye	79.1% decrease
ZRP	90.8% decrease

Adding the background traffic to the system shows a greater impact on number of packets received than the impact caused by increasing the number of aircraft nodes from 6 to 12. Each routing protocol shows a drastic reduction of performance when the background traffic is added to the system. While Fisheye and ZRP samples show a reduced number of packets received when the number of aircraft is doubled, AODV samples show a slight improvement.

Table A11. Packets received for 12-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
287	--	30	--
292	27	97	--
503	--	25	57
303	--	10	11
370	--	65	17
275	--	24	4
437	--	64	98
303	--	31	81
218	--	113	37
290	11	76	10

As shown in Figure A13, using AODV results in the highest number of packets received at the destination. The destination receives much fewer packets when Fisheye and ZRP are used.

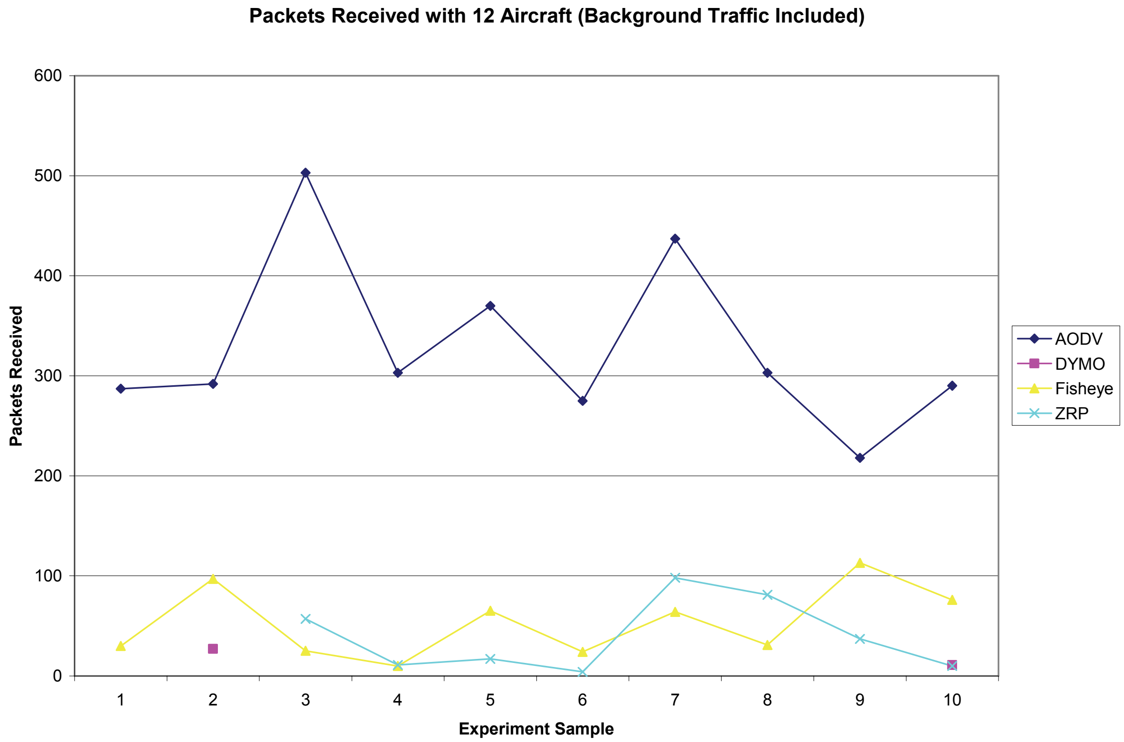

Figure A13. Packets received for 12-aircraft MANET with background traffic

A.2.3 Throughput

The throughput data for the 3-aircraft configuration with no background traffic is addressed in Section 4.3.1.

The throughput using the 3-aircraft configuration with additional background traffic is shown in Table A12 and plotted in Figure A14. Using only recorded data, mean values for throughput are:

AODV	47599 bps
DYMO	66914 bps
Fisheye	30476 bps
ZRP	30217 bps

Table A12. Throughput (bps) for 3-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
17947	--	8308	10419
63006	64527	14890	25200
66835	63481	24537	34261
23623	26012	--	8880
83836	79097	56531	58165
25444	--	2999	6343
83261	125009	127243	104023
47993	43355	14570	17182
16901	--	11404	21932
47147	--	13800	15768

As shown in Figure A14, DYMO and AODV samples show similar results, as do Fisheye and ZRP. DYMO and AODV consistently have higher throughputs than Fisheye and ZRP.

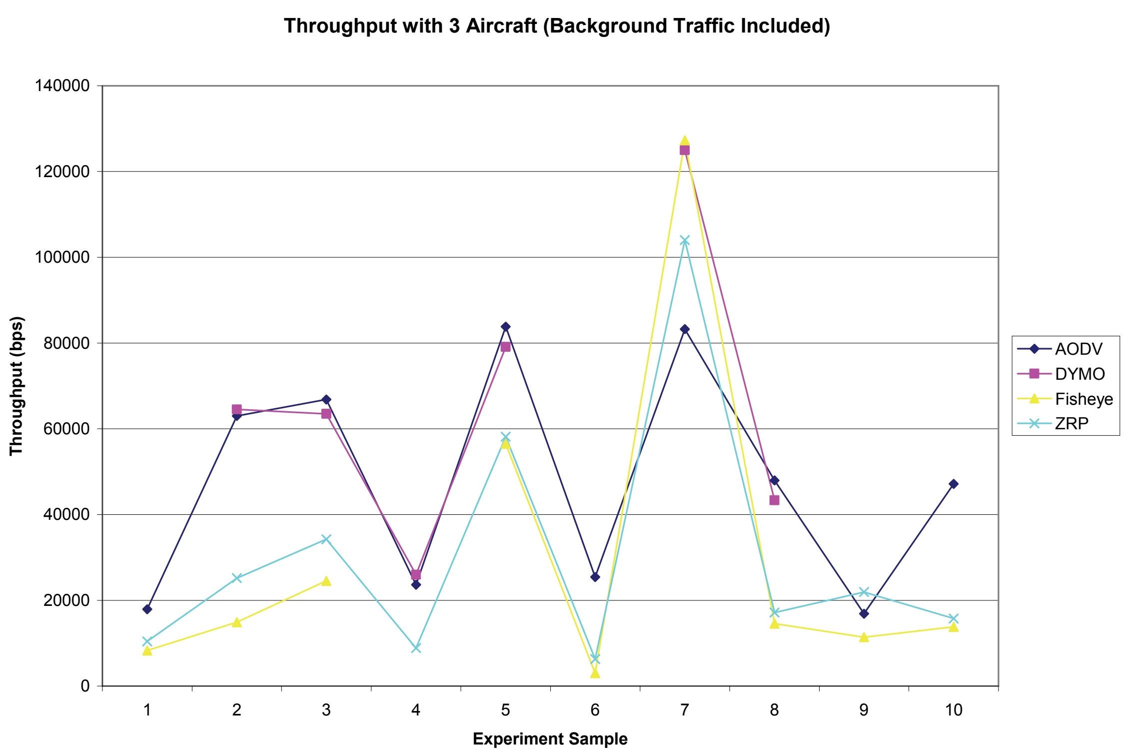

Figure A14. Throughput for 3-aircraft MANET with background traffic

The throughput using the 6-aircraft configuration with no background traffic is shown in Table A13 and plotted in Figure A15. Mean values for throughput are:

AODV	99828 bps
DYMO	101807 bps
Fisheye	40550 bps
ZRP	69501 bps

Table A13. Throughput (bps) for 6-aircraft MANET with no background traffic

AODV	DYMO	Fisheye	ZRP
133707	127076	51334	54574
92675	125186	47983	117807
95907	88927	49134	99000
42654	43598	23230	23412
122134	119891	29891	54166
76476	68779	30378	32554
100141	93522	31731	67621
135310	131255	33570	64572
98326	130937	64050	102201
100953	88898	44198	79099

As shown in Figure A15, DYMO and AODV samples show similar results and see the highest throughput values. The reactive protocols show throughput values higher than those of Fisheye, a proactive routing protocol. ZRP, a hybrid routing protocol, shows throughput samples consistently between the reactive and proactive routing protocol styles.

Compared to the throughput values observed in the 3-aircraft configuration with no background traffic, throughput samples are much more consistent when the number of aircraft is increased.

The throughput using the 6-aircraft configuration with additional background traffic is shown in Table A14 and plotted in Figure A16. Mean values for throughput are:

AODV	37314 bps
Fisheye	11068 bps
ZRP	8888 bps

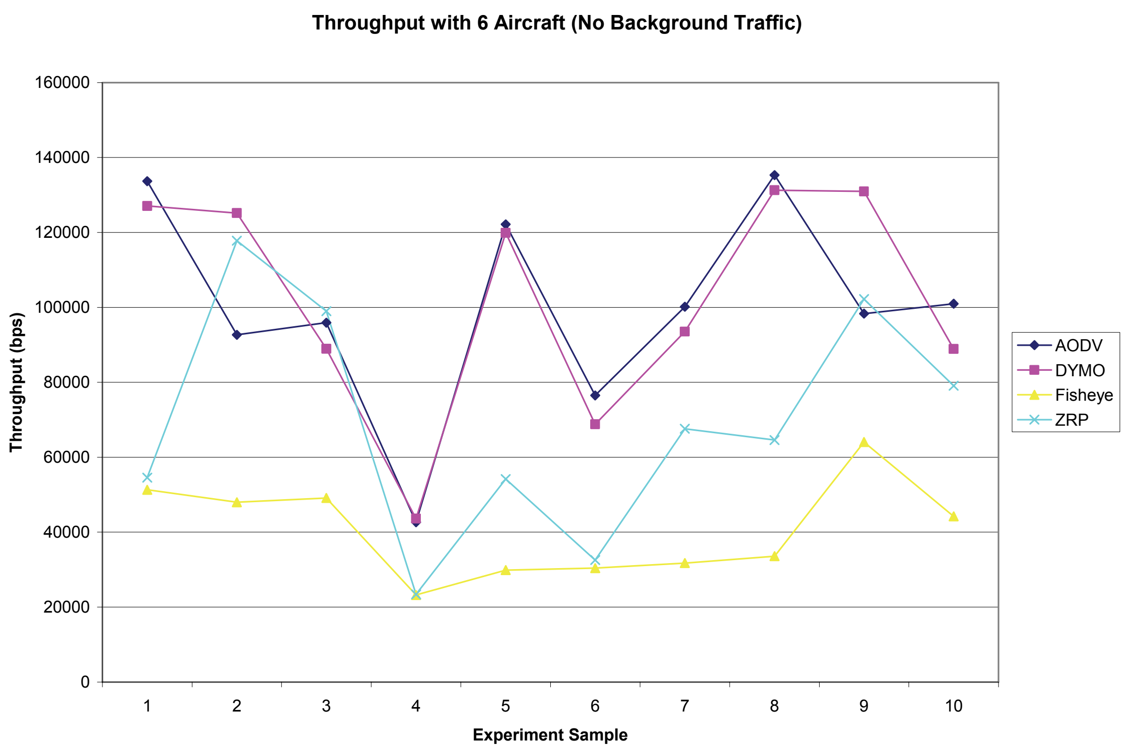

Figure A15. Throughput for 6-aircraft MANET (no background traffic)

Using mean values, compared to the throughput observed in the 3-aircraft configuration with background traffic included, the throughput decreases by the following percentage (impact of increased aircraft nodes):

AODV	21.6% decrease
Fisheye	63.7% decrease
ZRP	70.6% decrease

Using mean values, compared to the throughput observed in the 6-aircraft configuration with no background traffic, the throughput decreases by the following percentage (impact of additional load):

AODV	62.6% decrease
Fisheye	72.7% decrease
ZRP	87.2% decrease

Adding the background traffic to the system has a greater impact on throughput than the impact caused by increasing the number of aircraft nodes from 3 to 6, although this difference in impact is more noticeable with AODV (21.6% versus 62.6%).

While each protocol shows a decreased throughput, the reactive routing protocol shows the smallest decrease, followed by the proactive protocol, with the hybrid routing protocol showing the highest reduction in throughput for this configuration.

Table A14. Throughput (bps) for 6-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
23607	--	905	927
47381	--	16768	10935
60854	--	24825	17342
20349	--	952	2496
60169	--	10582	7676
32825	--	2562	345
50242	--	19439	24562
28068	--	3999	4388
14544	--	14446	7296
35096	--	16204	12917

As shown in Figure A16, using AODV results in the highest throughput. The throughput is reduced when Fisheye and ZRP are used.

The throughput using the 12-aircraft configuration with no background traffic is shown in Table A15 and plotted in Figure A17. Mean values for throughput are:

AODV	108654 bps
DYMO	102656 bps
Fisheye	30475 bps
ZRP	49026 bps

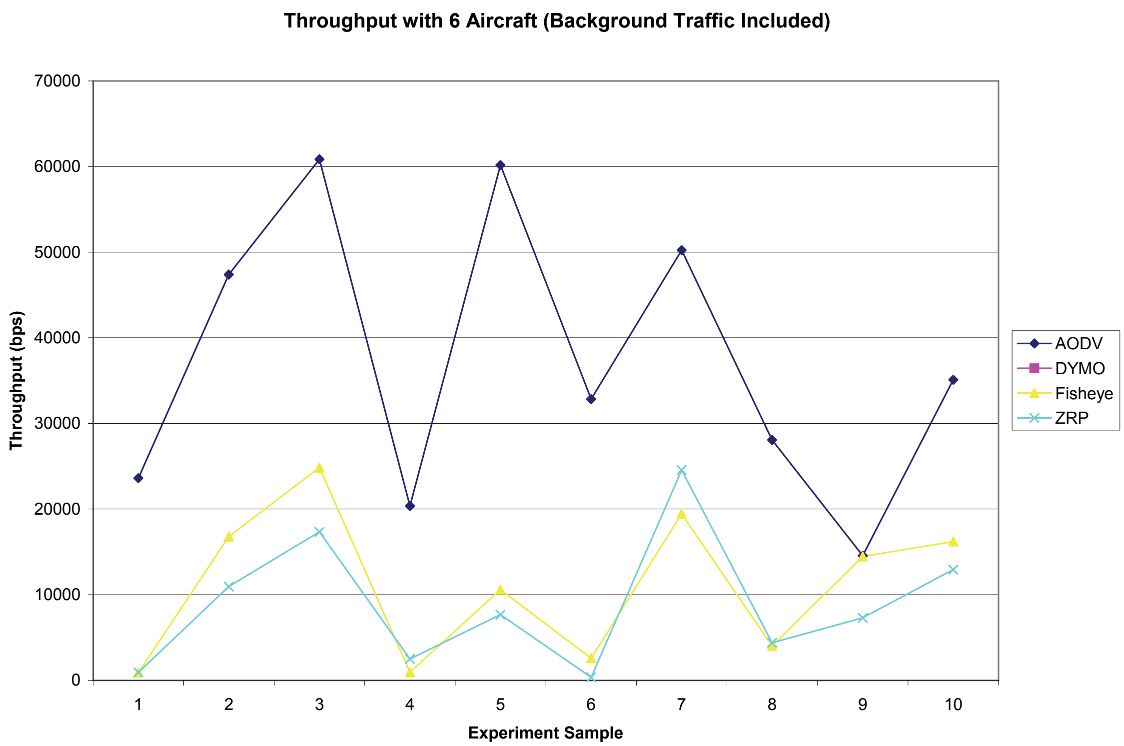

Figure A16. Throughput for 6-aircraft MANET with background traffic

Using mean values, compared to the throughputs observed in the 6-aircraft configuration with no background traffic, the throughput changes by the following percentage (impact of increased aircraft nodes):

AODV	8.8% increase
DYMO	0.8% increase
Fisheye	24.8% decrease
ZRP	29.5% decrease

Increasing the number of aircraft in the network from 6 to 12 causes the throughput to increase when using AODV and DYMO. However, Fisheye and ZRP throughput decreases with the addition of the aircraft.

Table A15. Throughput (bps) for 12-aircraft MANET with no background traffic

AODV	DYMO	Fisheye	ZRP
98043	91650	35065	45425
136269	87493	37544	52211
93908	93760	38651	48748
93523	95222	18170	35870
99475	139397	34845	54956
96490	91548	22476	54966
97347	96723	34050	56153
138796	96609	36675	67200
98556	97732	28857	42417
134135	136428	18421	32315

As shown in Figure A17, AODV and DYMO show the highest throughputs. The throughputs are lowest when Fisheye is used, with ZRP results falling in the middle.

The throughput using the 12-aircraft configuration with additional background traffic is shown in Table A16 and plotted in Figure A18. Using only recorded data, mean values for throughput are:

AODV	39107 bps
DYMO	3028 bps
Fisheye	6267 bps
ZRP	4918 bps

Using mean values, compared to the throughputs observed in the 6-aircraft configuration with background traffic included, the throughput changes by the following percentage (impact of increased aircraft nodes):

AODV	4.8% increase
Fisheye	43.4% decrease
ZRP	44.7% decrease

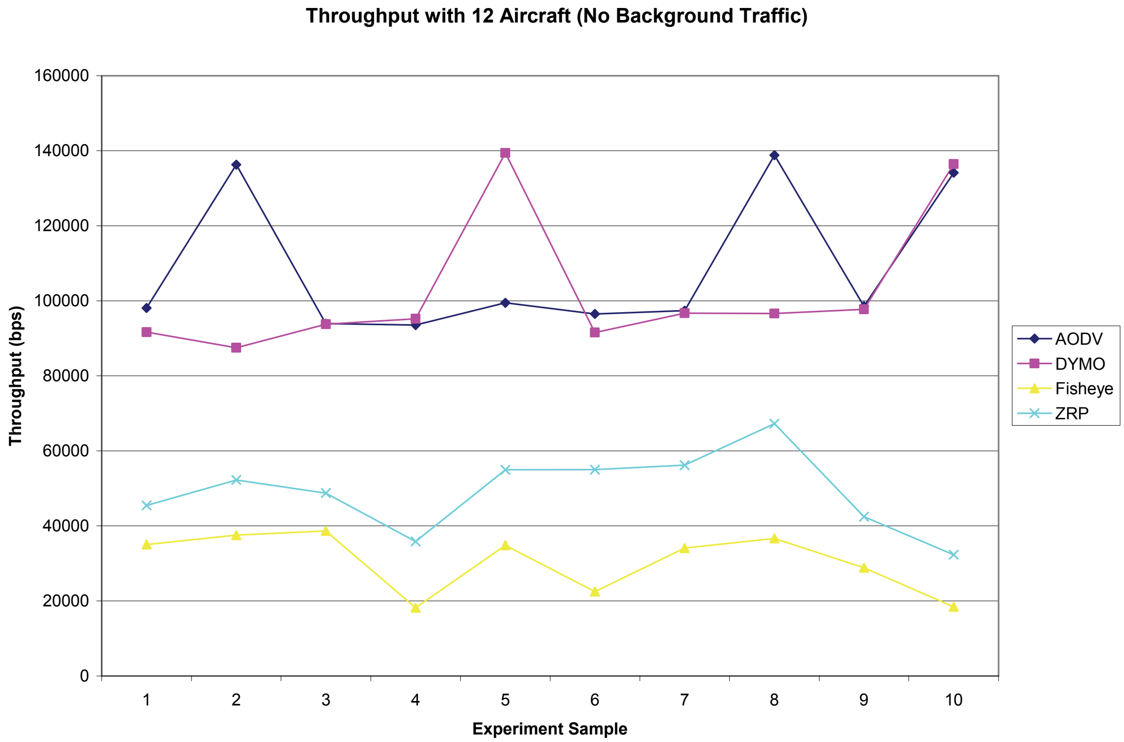

Figure A17. Throughput for 12-aircraft MANET (no background traffic)

Using mean values, compared to the throughputs observed in the 6-aircraft configuration with no background traffic, the number of packets received decreases by the following percentage (impact of additional load):

AODV	64.0% decrease
Fisheye	79.4% decrease
ZRP	90.0% decrease

Adding the background traffic to the system has a greater impact on throughput than the impact caused by increasing the number of aircraft nodes from 6 to 12.

Each routing protocol shows a drastic reduction of performance when the background traffic is added to the system. While Fisheye and ZRP show a reduced throughput when the number of aircraft is doubled, AODV shows a slight improvement.

Table A16. Throughput (bps) for 12-aircraft MANET with background traffic

AODV	DYMO	Fisheye	ZRP
32998	--	3452	--
33804	4686	11204	--
57830	--	2904	7503
48519	--	1168	1328
42550	--	7575	1955
31649	--	2812	464
50332	--	7462	12583
34969	--	3646	9330
25066	--	13266	5002
33357	1369	9182	1179

As shown in Figure A18, AODV samples show the highest throughput. Throughput is much lower when both Fisheye and ZRP are used.

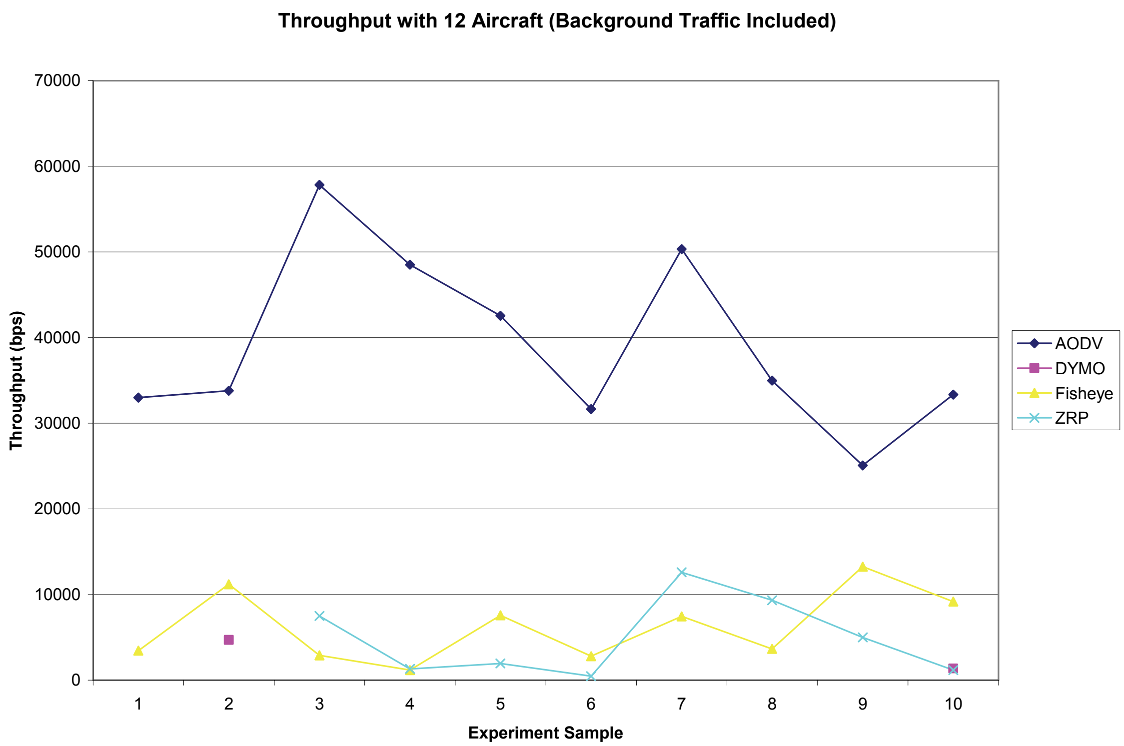

Figure A18. Throughput for 12-aircraft MANET with background traffic

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Vita

Daniel Roberts was born in Spokane, Washington, in 1975 and graduated from Broken Arrow High School, Broken Arrow, Okahoma in 1992. He was commissioned as a Second Lieutenant in the United States Air Force upon his graduation from the United States Naval Academy in 1996. While at the Naval Academy, he earned his Bachelor of Science degree in Electrical Engineering. He continued his education in the field of business and received his Master's degree in Business Administration from Oklahoma City University in 1999. While in the Air Force, he has worked as an avionics engineer on the AWACS aircraft, served as a test engineer for the Foliage Penetration radar, and worked as a developmental engineer on the Space-Based Infrared System. Upon graduation from the Air Force Institute of Technology, he will be stationed at Patrick AFB, Florida working at the Air Force Technical Applications Center.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE *(DD-MM-YYYY)*: 14 June 2007

2. REPORT TYPE: Master's Thesis

3. DATES COVERED *(From – To)*: March 2006 – June 2007

4. TITLE AND SUBTITLE

Performance Analysis and Comparison of Multiple Routing Protocols in a Large-Area, High-Speed Mobile Node Ad Hoc Network

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Roberts, Daniel K., Major, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)

Air Force Institute of Technology
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2950 Hobson Way, Building 640
WPAFB OH 45433-8865

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GE/ENG/07-28

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Air Force is interested in developing a standard ad hoc framework using "heavy" aircraft to route data across large regions. The Zone Routing Protocol (ZRP) has the potential to provide seamless large-scale routing for DOD under the Joint Tactical Radio System program. The goal of this study is to determine if there is a difference between routing protocol performance when operating in a large-area MANET with high-speed mobile nodes. This study analyzes MANET performance when using reactive, proactive, and hybrid routing protocols, specifically AODV, DYMO, Fisheye, and ZRP. This analysis compares the performance of the four routing protocols under the same MANET conditions. Average end-to-end delay, number of packets received, and throughput are the performance metrics used. Reactive protocol performance is better than hybrid and proactive protocol performance in each metric. Average ETE delays are lower using AODV (1.17 secs) and DYMO (2.14 secs) than ZRP (201.9 secs) or Fisheye (169.7 secs). Number of packets received is higher using AODV (531.6) and DYMO (670.2) than ZRP (267.3) or Fisheye (186.3). Throughput is higher using AODV (66,500 bps) and DYMO (87,577 bps) than ZRP (33,659 bps) or Fisheye (23,630bps). The benefits of ZRP and Fisheye are not able to be taken advantage of in the MANET configurations modeled in this research using a "heavy" aircraft ad hoc framework.

15. SUBJECT TERMS

Mobile ad hoc networks, routing protocols, Zone Routing Protocol, Fisheye State Routing, Dynamic MANET On-Demand Routing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	139	Barry E. Mullins, Ph.D.

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