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THESIS

MODELING A UAV-BASED MESH NETWORK TO ANALYZE LATENCY AND THROUGHPUT

by

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**MODELING A UAV-BASED MESH NETWORK
TO ANALYZE LATENCY AND THROUGHPUT**

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ABSTRACT

As the military has moved toward network-centric operations, unmanned aerial vehicles (UAVs) have become increasingly valuable for capturing real-time information for joint operations on the ground. These UAVs contribute to the mission by conveying the scene accurately to the decision maker. However, because of constraints in free space, using MANET with UAV nodes in free space that has no pre-existing infrastructure poses a network latency problem. Latency reduces network efficiency when transmitting real-time information to a ground station. One goal of analyzing latency is understanding the logic of the UAV network architecture and protocols. Specifically, the thesis investigates the following question: What are the effects of UAV altitude on MANET latency? To investigate this question, this research simulates a two-node UAV mesh network at 2,000 and 3,000 feet altitude using Riverbed Modeler Academic Edition software. The research finds that there is no significant difference in latency at these altitudes. Therefore, all else being equal, 3,000 feet is the preferred altitude for UAVs, as it allows observation of wider areas and reduces UAV vulnerability to enemy weapons without affecting latency.

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LIST OF ACRONYMS AND ABBREVIATIONS

AODV	Ad-Hoc On Demand Distance Vector
C2	Command and Control
DSR	Dynamic Source Routing
GCS	Ground Control Station
IFF	Identification Friend or Foe
IGP	Interior Gateway Protocols
IP	Internet Protocol
LAN	Local Area Network
MANET	Mobile Ad-Hoc Network
MIMO	Multiple Input Multiple Output
MPR	Multipoint Relay
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing
RIP	Routing Information Protocol
TCP	Transmission Control Protocol
UAV	Unmanned Aerial Vehicle
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

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I. INTRODUCTION

Several attributes inherent in electronic systems architecture contribute to issues in using these systems today. Enhancing the capabilities of electronic systems, in particular, requires reinforcing the command and control cycle and supporting the frontline mission. A friendly fire incident in northern Iraq on 7 April 1991 displayed several problems that arise with electronic systems architecture in this regard: F-15 fighters shot down a U.S. Blackhawk in a no-fly zone area due to the failure of the IFF (Identification Friend or Foe) system, among other failures. As Scott A. Snook (2011) noted in describing the complexity that contributed to the mishap, “each with its own helicopters and fixed-wing aircraft, the challenge became one of putting them all back together again, on the same battlefield, sharing the same air space” (p. 155). Managing complex flight capabilities systems requires building efficient systems architecture. This efficient systems architecture requires a comprehensive and integrated effort, to reduce human error caused by electronic systems today in various military operation services. This challenge of integration necessitates standardization of electronic systems to run all systems efficiently as one, which in turn requires researchers and engineers to agree on electronic specification and standardized military aviation capabilities.

While aviation has changed since the friendly fire incident, the issue of how to design an aviation electronics system architecture that integrates with other aviation systems in battle still remains. In particular, as the military moves toward network-centric operations, unmanned aerial vehicles (UAV) will be valuable for capturing real-time information for joint operations on the ground; these UAVs facilitate the mission by conveying the scene accurately to the decision maker. In light of the technological progress of the armed forces, UAVs have become active weapons that support the front lines in battle by tracking the movement of the enemy on the battlefield. Since more battles occur in constrained areas, where it is difficult to transmit information over fixed networks, using UAVs’ ad-hoc networking communication architecture in these areas is a challenge. There are several ways to integrate communication architecture to connect multiple UAVs in a mesh network, but network latency affects the quality of battlefield information transfer

via the UAV. The same is true for situational awareness views at the operations centers: network latency has a negative impact on decision makers in the theatre of operations. In constrained areas, operators use UAVs to support mission achievement through reconnaissance to detect the position of the enemy in battle. Therefore, a delay in signal communication between UAVs and the ground station will impact ground forces' movement; commanders will not have enough information about the situation on the ground to guide or inform ground forces to attack or defend, which can cause loss of position and loss of land, as well as increase the possibility of casualties.

Therefore, defending communication devices and ensuring communication among forces requires having alternative plans. The military needs an adaptive flexible network architecture to reduce vulnerability arising from latency. According to Harris Corporation (n.d.), "The future is about ensuring spectrum-wide superiority at all times, in all domains." This indicates that future wars will require ensuring performance of packets in the network and providing a real-time picture to avoid lack of communication in battlefield environments. Therefore, network topology, network architecture, wireless propagation, network routing, network performance, and network applications are all needed to face this phenomenon. These technologies facilitate the exchange of information among nodes and also defend network capabilities in the operational theater for continued transmission.

Although some research has been conducted in the area of reinforcing signal strength between UAVs to ensure that wave propagation—in other words, network performance—endures, the question remains of what type of network architecture maximizes signal performance in the face of constraints. This requires a network technology capable of facilitating electronic integration among various systems to establish efficient coordination. Given these requirements, network technology through effective systems architecture can ensure communication between a ground station and multiple UAVs' nodes to reinforce network and telecommunication technology in mesh networks.

This research focuses on the effect of the UAV nodes' altitude from a ground station on wireless performance within mesh network. Decentralized mesh networking topology indirectly supports UAV communication through an intermediate UAV. Altitude creates unstable network performance because of UAV speed and movement in free space that

affect the antenna orientation, which in turn affects performance in this network. In order to reinforce the strength of ground forces, and support front line missions, it is necessary to maintain the connectivity of UAVs and the continuous transmission of information between UAVs and the ground station; it is therefore critical to understand what UAV altitude enhances network performance and minimizes mobile ad hoc network (MANET) latency.

A. RESEARCH QUESTIONS

To determine which altitude in a MANET application better supports throughput and reduces latency, this thesis investigates the following questions:

What are the effects of UAV altitude on MANET latency?

Which of the preferred altitudes is better to use for minimizing UAV MANET latency?

B. METHODOLOGY

To investigate these questions, this research simulates a two-node UAV mesh network using Riverbed Modeler Academic Edition software. This software allows the researcher to establish UAV nodes configuration and set different parameters such as distance (kilometres, Km), altitude (feet), UAV maximum speed, and radio protocols. These attributes enable the researcher to measure the performance between the ground station and UAV nodes maintaining signal strength within the mesh networks.

C. HYPOTHESIS

The initial hypothesis of this research is that as altitude increases latency between the ground station and the UAV nodes will increase due to several factors that affect the signal power strength, particularly the energy efficiency. The greater the altitude of the UAV, the more power is required for flight maneuver, which leaves less power available to maintain signal strength and creates higher latency.

D. SCOPE AND LIMITATIONS

The following limitations apply to this research:

- Security is important to secure packet transmission in MANET, but it is not a subject of this research, which focuses on network architecture.
- Classified UAV (such as the Boeing ScanEagle used in this research) flight and radio capabilities information prevent the researcher from identifying the exact capabilities of the UAV's nodes; thus, some assumptions have to be made about the properties of the UAV nodes.
- Although several routing algorithm protocols can be used in mesh networks, this thesis focuses on Dynamic Source Routing (DSR) because it selects the route that must be used in transmitting data to its destination.
- A UAV icon was not available in the simulation, but the researcher utilized his laptop so as to represent the UAV.
- Omnidirectional antenna parameters were not available for MANET station (Mobile nodes) attributes, in particular; therefore, this model assumes an omnidirectional antenna.

E. THESIS OUTLINE

The remainder of this thesis is organized as follows: Chapter II provides the literature review, while Chapter III discusses the methodology used in the simulation, and Chapter IV interprets the results of the simulation. Chapter V offers the lessons learned, recommendations, conclusions, and suggestions for future work. The appendix contains a template for further simulation.

II. LITERATURE REVIEW

Determining what altitude from the ground station minimizes network latency within MANET and reinforces a UAV's signal strength in free space intersects with many network-related issues. This section begins with a related literature review and a discussion of network topology types and how topology maintains a network. The chapter then discusses network layer relevant to latency, including free space propagation, radio protocols, routing algorithm, network architecture, Transmission Control Protocol (TCP), and performance metrics. Finally, it examines the role of the network manager in investigating the health of network.

A. RELATED LITERATURE

In previous studies, researchers investigate the capabilities of network performance and examine the coordination and communication among the network operator and nodes. These researchers focus on how to manage Command and Control (C2) in various missions in maritime and front-line forces such as Special Forces by utilizing a MANET topology capable of directing a signal among nodes or a military operation center. As Matthew S. Maupin (2016) noted in his research, the complexity of C2 in littoral environments creates an unstable operating environment. Maupin's thesis identified the complexity of littoral environment and its real impact on C2 performance and MANET management of littoral operations, by focusing on human factors as the main resource to control several nodes.

While coordination and other human factors responsibilities are critical to network management, effective coordination is only possible through reliable network performance. And, reliable network performance is only possible through good network architecture. Building on Maupin's thesis, the aim of the present thesis is to guide decision makers to a clear picture to distinguish the cause and effect of packet latency in networks, using network architecture software. As Maupin noted, "the open architecture design of new network management systems like Code Mettle provide significant flexibility and adaptability to evolve with improvement in technologies and capabilities" (p. 85). Thus, improving C2 capabilities and communication among nodes in a network requires

predicting and modeling the architecture of the network through simulation to determine the efficiency of signals between ground stations and UAV nodes in a mesh network in preparation for facing constraint in free space.

B. NETWORK TOPOLOGIES

The physical arrangement of the network architecture components is called the topology. There are a number of network topology types relevant to this research, including fixed and ad-hoc network architectures, which are described in the following paragraphs.

1. Fixed (Infrastructure) Network

A fixed network is a physical network built in a local area and consists of fixed network elements such as routers, switches, and servers to support nodes within this network. Use of a fixed network speeds data transmission between nodes, because fixed infrastructure like the operating center, communication towers, microwave dish, and other telecommunication stations and network elements support data transmission among these nodes.

Network managers are able to manage fixed networks with a command prompt application. Utilizing the command-line interpreter features in Windows or MAC operating systems, network managers can solve node failures and other issues that reduce network performance. This command-line interpreter assists network managers to track a network issue, failure of nodes, data transmission speed, traffic, and other bottlenecks occurring in a local area network (LAN) or wireless area network, which saves time and effort in investigating that status of network nodes such as computers, laptops, routers, and switches and fixing the issue through the command prompt application.

The command line interpreter is a useful tool to monitor network element status; however, human intervention might be needed to fix media failures related to cabling, network interface cards, connectors, and other issues. Indeed, the benefit of a fixed network is that network administrators are able to configure network elements more simply than in other networks that require software tools to fix technical flaws. As fixed networks consist of network elements on the ground, the maintenance of these devices is much simpler.

2. Ad-Hoc Mobile Network

Whereas fixed networks use physical infrastructure to maintain communication among devices, ad-hoc wireless network topology uses peer-to-peer connections to maintain node-to-node telecommunication in free space. According to Bradley Mitchell (2018) in an online article, “A Wi-Fi network in ad-hoc mode (also called *computer-to-computer* or *peer* mode) lets two or more devices communicate with each other directly instead of through a central wireless router or access point (which is what infrastructure mode is).” This arrangement is significant in that ad-hoc network topology does not rely on a single backbone to provide the signal to sustain link state in the network. Rather, ad-hoc networks are built to support nodes without using any additional physical infrastructure to sustain link state. According to Mitchell, “an ad-hoc network is useful if there isn’t a wireless structure built.” This feature of ad-hoc networks keeps a network effective and also provides integration among the nodes without any network infrastructure such as communication towers, microwave receivers, or any backbone that supports signal and link state in the network.

Using an ad-hoc network has several other benefits. First, ad-hoc networks reinforce telecommunication between nodes. According to James T. Wood (n.d.), “running an ad hoc network can be more affordable than a traditional network—you don’t have the added cost of a router.” In other words, using an ad hoc network saves enterprises money. Also, avoiding the use of a router means no router will need maintenance. Second, ad-hoc networks enable telecommunication in various situations and circumstances where a fixed network does not exist. According to Wood, “Ad hoc networks can be created on the fly in nearly any situation where there are multiple wireless devices.” Significantly, this property means that ad-hoc networks can assist in maintaining communication signal strength and sustaining network stabilization without the aid of network infrastructure other than the nodes themselves.

C. NETWORK LAYER OVERVIEW

The network modeled in this research is an ad-hoc UAV network. As in all networks, UAV networks are made up of seven layers to establish the telecommunication capability, as shown in Figure 1. This research focuses on Layer 1, Layer 2, Layer 3, Layer

4, and Layer 7, as these are the layers in which latency occurs. In Layer 1 (Physical Layer), the bits of data transfer through fields, such as the electrical and electromagnetic fields, to access various channels within the network. Next is Layer 2 (Data Link), which controls the information and ensures that this information reaches its destination, either in the WAN or among nodes in the LAN. Specifically, this thesis utilizes the MANET topology among UAVs to exchange information. The purpose of Layer 3 (Network) is to guarantee the packet flow through network devices, to enhance the network performance, and to maintain network capabilities in regulated data frames, without any changes in data frame size. Layer 4 (Transport) allows for the verification that packets reach their destination, and the resending of packets in case of transmission failure. The software that the network manager utilizes to check the health of the network resides in Layer 7 (Application).

This research utilizes these layers to investigate telecommunication among nodes depending on a UAV's altitude to establish a baseline comparison of latency. Investigation of these layers supports network managers analyzing telecommunication among UAVs' nodes and a groundstation, which requires the configuration of various nodes in a mesh network to establish the traffic flow among nodes. The network manager investigates the latency within this network relying on simulation software that is used to represent network performance.

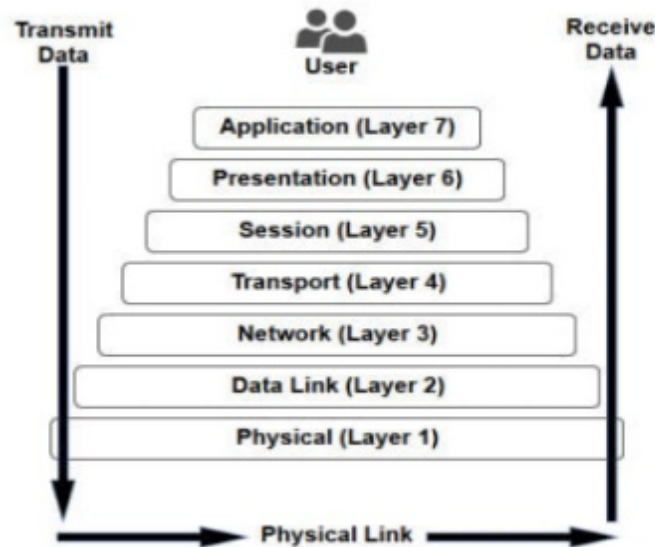


Figure 1. The 7 Network Layers. Adapted from Beal (2018).

The following sections describe the relevant network layers.

D. LAYER 1 IN UAV NETWORKING: WIRELESS SIGNAL PROPAGATION

Wireless propagation is an important factor to support signal strength and maintain link states to minimize latency in free space propagation. Wireless propagation supports nodes through the electromagnetic spectrum to reinforce signal communication. According to Mani Subramanian (2011), “there are several physical mechanisms to consider in dealing with wireless propagation, which we do not have with propagation through wired networks” (p. 558). One of those considerations is antenna orientation and efficiency. Also, as was discussed previously, a fixed network is stable, whereas ad-hoc networks face constraints that limit their efficiency. When operating within an ad-hoc network, nodes will receive a less stable signal than in a fixed network because there are several factors that limit wireless propagation, such as weather, buildings, and trees, and other constraints that create transmission obstacles in a network, reducing the performance of signal transmission and causing packet delay. By contrast, the omnidirectional antenna offers a solution to receive the signal from different antennas.

The following sections discuss the wireless propagation environment and relevant antenna properties.

1. Propagation Environment

There are various types of wireless propagation environments. The two most relevant to this research are free-space propagation and urban wireless propagation, discussed in the sections that follow.

a. Free-Space Propagation

Free-space propagation propagates in multiple areas without physical infrastructure to maintain signal strength. One important property of free-space propagation is that it becomes weaker as the distance among nodes increases. Free-space wireless propagation depends on neighboring nodes' signal to reinforce the efficiency of wireless propagation between UAV nodes. UAV nodes can act as both transmitter and receiver, and free-space

propagation among UAV nodes is affected by the dynamic, constantly changing distance and height of the UAVs, as well as other constraints that limit signal strength. These constraints differ according to the UAV mission that requires different UAV behaviors in free space.

Because these dynamic changes occur in free-space wireless propagation, it is necessary to rely on a laser communication system to reinforce the capabilities of ad-hoc network performance. As Hassaun A. Jones-Bey (2007) noted, the usefulness of a “wireless laser-communications system [is its ability] to obtain a reliable, high-capacity optical link through the cloud” (para. 4). The purpose of the laser communication in free space is thus to ensure propagation spread out among the UAV nodes at different distances and altitudes, and under different constraints.

b. Urban Propagation

Several issues limit wave propagation in urban areas, such as reflection, refraction, and diffraction, which cause packet delay and reduce UAV nodes’ signal performance in these environments.

(1) Reflection

In determining the performance of wave propagation, it is important to focus on factors that degrade communication to reduce incidents occurring among different antennas—in the case of this research, between UAV nodes. One important factor that affects urban propagation is reflection, loss of energy because of weather or natural factors. According to David R. Frieden (1988), “often energy is lost from the incident wave because of the presence of natural obstacles such as dust, snow, or water vapor” (p. 18). Such obstacles reduce signal distribution, allowing only part of the transmission to reach its destination. How much of the signal passes through obstacles depends on the resistance coefficient of the materials involved, such as water, glass, cement, wood, metals, and other materials that limit propagation in urban environment.

There are two methods for addressing the reflection in urban environments, Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO), which reduce reflection of signal and provide solutions to assist signal strength.

Orthogonal Frequency Division Multiplexing

OFDM spreads signal information to multiple frequencies, which enables a transmission to reach various nodes within the network and smooths the transmission. OFDM is a multicarrier modulation that utilizes various frequencies to ensure that the information reaches its destination despite obstacles. OFDM is therefore able to carry frequency and facilitate transmission of information such as data and voice to the nodes. This multicarrier modulation also mitigates interference between multiple signals because of modulation's ability to add a sampling window and guard interval. This maintains signal strength among various information sub-carriers in a system and provides a solution to ease the impact of natural reflection. Control of the sampling window and guard interval increases the system's ability to send the signal to the destination and reduce the effect of reflections by allowing the guard interval to maintain the signal strength of losing the pattern of waves.

Multiple Input Multiple Output

There are many theories to describe the MIMO method, but this section describes specific diversity techniques utilized in MIMO. MIMO is a method to direct signal flow by identifying multiple channels to reduce interruption and mitigate the effect of reflection on the signal. Use of the diversity techniques enables protecting the network from propagation fading that occurs from reflection obstacles. Methods such as spatial diversity provide more than one physical path to stabilize communication while frequency diversity allows for transmission on more than one frequency to reduce channel interference. Coherence time is used to maintain the electromagnetic wave for a long time and balance the response time in various channels that control the signal wave. These techniques of diversity effectively treat traffic jams that occur in telecommunication among nodes, particularly among UAVs that fly in urban areas.

(2) Refraction

Refraction occurs when an electromagnetic wave transmits in free space. During refraction, the wave changes direction as it moves through different media or the medium itself changes. This phenomenon also depends on density of air: according to Frieden (1988), “an electromagnetic wave encounters several variations in air density” (p. 20), and density of the air changes the direction of propagation of the wave. Refraction creates constraints to wave propagation that impact signal pattern shape, which can create latency.

(3) Diffraction

Diffraction occurs when an electromagnetic wave changes direction because of the edge on obstacles. According to The Physics Classroom website (n.d.), “diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path.” Such changes affect the performance of a signal: while they do not limit the transmission overall, they do diminish the efficiency of a wave by bending the wave. Also, when amplitude increases bending of wave increases depending on the medium’s density, which scatters the wave and causes transmission latency.

2. Antenna Efficiency

Latency among UAV nodes in free space is impacted by antenna efficiency. Path loss formulas are used to determine various capabilities of radio communication systems such as transmitter power, received power, gain, locations, and height. This determination identifies signal strength among various antennas and assists network managers to observe sensitivity of electromagnetic waves during signal transmission. These formulas also indicate the power requirement to enhance signal strength and allow network managers to position antennas, including UAVs, in appropriate locations to ensure signal quality.

Because the focus of this research is on antenna efficiency performance to determine UAVs’ network architecture to minimize MANET latency, it measures loss of path in terms of dB. The formula for determining path loss (L_{path}) is given in Equation 1:

$$L_{path} (dB) = 32.44 + 20 \log_{10} (f_{MHz}) + 20 \log_{10} (L_{km})$$

This formula shows that path loss between transmitter and receiver increases as distance and frequency increase.

Another important measure of antenna efficiency is polarization: “polarization of a plane wave is the figure the...electric field traces out with time” (Stutzman & Thiele, 1998, p.48). It is necessary to have identically polarized antennas to reduce the disruption and loss of signal between transmitter and receiver. Table 1 shows how polarization efficiency depends on antenna type. If the antenna polarization is the same then signal will be received at maximum power, but if the antenna polarizations are different there will be some amount of power loss depending on the antenna orientation. This factor allows the network manager to understand how various polarizations might increase latency and reduce overall network performance in a military mission.

Table 1. Degree of Gain between Antennas of Various Polarizations.
Source: De Vita (2012).

Transmit antenna polarization	Receive antenna polarization	Ratio of power received to maximum power	
		Ratio	Ratio [dB]
Vertical	Vertical	1	0
Vertical	45 or 135 degree	$\frac{1}{2}$	-3
Vertical	Horizontal	0	$-\infty$
Vertical	Circular (right or left)	$\frac{1}{2}$	-3
Horizontal	Horizontal	1	0
Horizontal	45 or 135 degree	$\frac{1}{2}$	-3
Horizontal	Circular (right or left)	$\frac{1}{2}$	-3
Circular (right-hand)	Circular (right-hand)	1	0
Circular (right-hand)	Circular (left-hand)	0	$-\infty$
Circular (right or left)	45 or 135 degree	$\frac{1}{2}$	-3

3. Omnidirectional Antenna

This research assumes that UAV nodes are equipped with an omnidirectional antenna. Whereas directional antennas must be oriented toward each other to receive signal, omnidirectional antennas radiate signal from any direction without relying on specific antenna orientation. This radiation of signal allows ground stations to receive a UAV's

omnidirectional antenna electromagnetic wave as the UAV's speed and position change in maneuver. This antenna, therefore, is essential for the UAV's command and control.

E. LAYER 2 IN UAV NETWORKING: PROTOCOLS (802.11)

While Layer 1 focuses on physical properties of the wave, Layer 2 enhances the physical layer capabilities by providing radio protocols (802.11). The 802.11 protocol ensures communication in the physical layer through half-duplex signaling to reinforce the efficiency of bit rate performance within the wireless mesh network.

Furthermore, there are different standards of 802.11 that maintain telecommunication. In particular, using 802.11n supports the network manager to obtain a realistic gain and high-speed bit rate per second that limits the loss of data frames. As Jill West, Tamara Dean, and Jean Andrews (2016) note, "802.11n boasts maximum throughput of 600 Mbps, making it a realistic platform for telephone and video signals" (p. 292). Given that efficiency enhances the performance quality of the network through a high max throughput between transmitter and receiver, this efficiency might reduce the packet delay among various nodes depending on distance and other obstacles that limit efficiency of bit rate throughput.

Furthermore, 802.11n operates in various frequencies such as 2.4 GHz and 5.0 GHz. In 2.4 GHz, the 802.11n standard enables high cover frequency range, which is applicable for use in a limited military operations mission in an urban environment. On other hand, using 5.0 GHz frequency reduces the range of frequency coverage, but it maintains high-speed bit rate. As NETGEAR Support (2019) notes, "The range is lower in the 5 GHz band because higher frequencies cannot penetrate solid objects, such as walls and floors. However, higher frequencies allow data to be transmitted faster than lower frequencies, so the 5 GHz band allows you to upload and download files faster." Since 5 GHz is adversely affected by obstacles, 2.4 GHz remains a solution to indoor and outdoor wireless signal propagation that enables reinforcement of the efficiency of the network during an urban operation. Thus, this research uses 802.11n at 2.4 GHz.

F. LAYER 3 IN UAV NETWORKING: NETWORK ROUTING

Network routing algorithms sustain communication among nodes by directing signal path in the physical layer. The two foundational types of network routing are static and dynamic.

1. Static Routing

Static routing is fixed routing that links nodes directly without relying on alternative algorithms to determine shortest path to identify neighboring nodes as dynamic routing does. Static routing is used in fixed networks as the routing protocol to identify routers. InetDaemon (2018) noted that “static routing is simply the process of manually entering routes into a device’s routing table via a configuration file that is loaded when the routing device starts up.” This fact is significant in that all data about routing protocols in static routing is configured manually by the network administrator based on the expected parameters for how a router will identify a neighbor router and transmit packets. Moreover, according to the IBM Knowledge Center (2010), “static routing usually takes advantage of default routes: when the destination is not explicitly coded, [packets are sent] to the default router and let that router figure out how to get the packet to its destination.” This indicates that static routers choose the shortest path to the destination; when a static router does not know the destination, it chooses the default router, prompting other routers to investigate the next destination since the exact destination is unknown, to discover the appropriate route and deliver the transmitted packet. Additionally, according to Cisco (2018), “static routes use less bandwidth than dynamic routes, as packets transmit along a fixed path rather than many variable paths, which provide adequate space to other routing code during the information transfer process.

2. Dynamic Routing

Dynamic routing is an algorithm used to identify the shortest path from node to node to mitigate signal constraint among nodes in a network. Dynamic routing makes use of alternative plans to identify the shortest path to reach neighbor routers to maintain network communication. According to Sudip Misra and Sumit Goswami (2017), “dynamic routing allows routing tables in the routers to change so as to enable the best alternative

route available at any instance of time to be chosen as the possible routes change” (p. 67). That is, dynamic routing schemes allow routers to predict various methods to enhance the direction of routes in case of router failure and thus maintain telecommunications connectivity. This is unlike what occurs in static routing, where, if a router is down, the process of exchanging information breaks, halting transmission of data through network elements.

Additionally, dynamic routing depends on gateway protocols that facilitate reaching nodes or other network elements. These protocols are the basic engine of data transmission and include Interior Gateway and Exterior Gateway protocols. The Interior Gateway protocols (IGP) focus on an individual domain to analyze and determine the shortest path among network elements in this domain to smooth data transmission throughout this domain. According to Misra and Goswami (2017), “Each individual network also uses an IGP for shortest path determination within its own routing domains” (p. 68). IGP thus focuses on shortest-path determination in the inner domain to protect the internal communication from barriers that limit communication. The Exterior Gateway protocols (EGP) depend on discovering the nodes or network elements based on distance. According to Misra and Goswami, “EGPs propagate ‘reachability indications’ in terms of many different attributes to measure routes and not the true metrics” (p. 68). This means that EGPs focus on distance to find the shortest path rather than focusing on routers’ availability in a domain. This reduces time and enables information exchange among routers.

a. Routing Algorithms Protocols

The protocols’ purpose is to enhance network routing and stabilize signal transmission. Various protocols such as Optimized Link State Routing Protocols (OLSR) and Ad-hoc On-demand Distance Vector (AODV), and DSR (Dynamic Source Routing), facilitate information exchange and mitigate delays occurring in ad-hoc networks.

(1) Optimized Link State Routing Protocols

There are several protocols used in networks to maintain connectivity among UAV nodes. One of the most important protocols used to sustain network communication

between nodes is OLSR. This protocol enhances the packet transmission among nodes and reduces the time to transmit packets in an ad-hoc network. According to Abdel Ilah Alshabtat and Liang Dong (2011), OLSR “reduces the size and the number of the control packets” (p. 991). This means that OLSR is built to control packets among the nodes to maintain network performance in ad-hoc networks and to enable packet transmission.

One type of OLSR protocol, multipoint relay (MPR), plays an important role in transmitting and receiving packets in OLSR. According to Alshabtat and Dong (2011), “MPR is a node chosen by another node that is willing to transmit its data” (p. 991). This means that MPR creates integrated information exchange among nodes. This property reduces delay times in packet transmission because nodes receive a packet and retransmit the packet to the source.

Figure 2 shows how UAVs communicate with each other using MPR. It shows that MPR’s role is to sustain the connectivity among UAV nodes to enhance packet transmission. Also, it shows that the source (upper left) can reach the destination and exchange information through MPR, which allows transmitting and retransmitting the packet among nodes in an ad-hoc network. Also, this topology retains flexibility in packet movement and reduces packet loss.

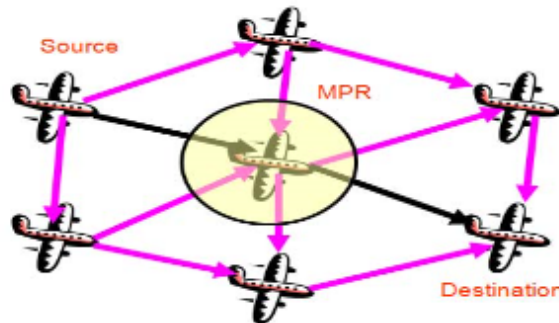


Figure 2. Multipoint Relay (MPR). Source: Alshabtat and Dong (2011).

(2) Ad-hoc On-demand Distance Vector

The role of the AODV routing protocol is to audit routing table information and avoid routing loops. According to Prashant K. Maurya, Gaurav Sharma, Vaishali Sahu,

Ashish Roberts, and Mahendra Srivastava (2012), “it uses traditional tables, one entry per destination, and sequence number to determine whether routing information is up to date to prevent routing loops” (p. 728). This means that AODV is responsible for reducing routing loops between sources and destinations to maintain and sustain network routing. Also, this protocol, by using sequence number, notifies neighboring nodes about any information that is not up to date in case they receive old information. This notification will result in the nodes’ not accepting expired information to avoid additional loops and prevent packet latency among nodes.

There are, however, several drawbacks to using AODV, such as expiration of active routes and difficulties receiving and maintaining routing information. According to Maurya et al. (2012), “Determining of [sic] a reasonable expiry time is difficult” (p. 728). This means that circumstances and constraints affect the AODV protocol’s effectiveness at managing and controlling complex changes in routing algorithms in case an active route expires suddenly or an event occurs to those nodes during the routing process. Moreover, AODV presents some shortcomings to maintaining routing information. According to Maurya et al., “AODV can gather only a very limited amount of routing information” (p. 731). Therefore, the data flow capacity of AODV protocols is low, which diminishes the efficiency of routing information maintenance that supports neighboring nodes in obtaining and identifying updated routing information to initiate communication.

(3) Dynamic Source Routing

Utilizing DSR as the ad-hoc routing protocol for UAV nodes maintains the nodes’ configuration and route path. According to David B. Johnson, Yih-Chun Hu, and David B. Maltz (2007), “DSR allows the network to be completely self-organizing and self-configuring, without the need for any existing network infrastructure or administration.” This indicates that DSR is capable to maintain network and transmission data in different circumstances, without the intervention of a network manager. This capability of DSR that relies on multi-hop wireless communication allows nodes to observe neighboring nodes and maintain the nodes’ configuration easily within a mesh network, which enables the sender (UAV nodes) to control the path of packets. This dynamic routing reduces latency

and facilitates information flow in a mesh network, which reinforces dynamic algorithm routing within MANET and supports ad-hoc network capabilities in large-scale networks. This thesis uses DSR in network simulation.

3. Network Architecture

The previous section focused on the condition when two nodes are communicating. This section discusses communication among multiple nodes. Network managers rely on the previous parameters to measure various constraints on network operation during communication. Based on these measurements the network manager decides which network architecture to use. Network architecture is the schema to identify which topology is suitable given various complex changes in the network. There are two major types of UAV network architecture: centralized UAV network, decentralized UAV network.

a. Centralized UAV Network

Centralized UAV network architecture is one of many topologies to support and maintain a link between the ground station and UAVs in the sky. The responsibility of the ground station is to transmit real-time pictures provided by the UAVs to a military operation center. This topology connects UAV nodes directly to the ground station, as shown in Figure 3.



Figure 3. Centralized UAV Network Architecture. Source: Li, Zhou, and Lamont (2013).

Within this topology, if the ground station fails to support nodes, connectivity will disappear, which will destabilize the transmission lines and affect C2 strategies, plans, and decisions. Moreover, “advanced radio transmission devices with a high transmission power are required in the UAVs, which may not be practical for medium or small UAV’s due to their size and payload constraints” (Li, Zhou, and Lamont, 2013, p. 1416). Network managers must ensure that UAVs include high enough transmission power to maintain their links with the ground station to avoid power loss.

b. Decentralized UAV Network

Decentralized UAV network architecture is a topology that supports UAVs through multiple sources to ensure connectivity and enhance overall communication among UAVs in free space. This topology relies on dynamic routing, which can manage rapid changes occurring in the network and limit failure events that delay packet transmission and affect performance of transmission. In this topology, a backbone UAV behaves as a mobile ground station, and it is used to maintain signal in free space. A network operator in the ground station can utilize the backbone UAV to keep signal strength at high efficiency to enable UAVs to continue transmitting signal in areas without infrastructure. Moreover, the backbone UAV becomes a solution for processing and strengthening the signal if bandwidth decreases because a bottleneck occurs in the network. Figure 4 shows how the backbone UAV supports signal strength.

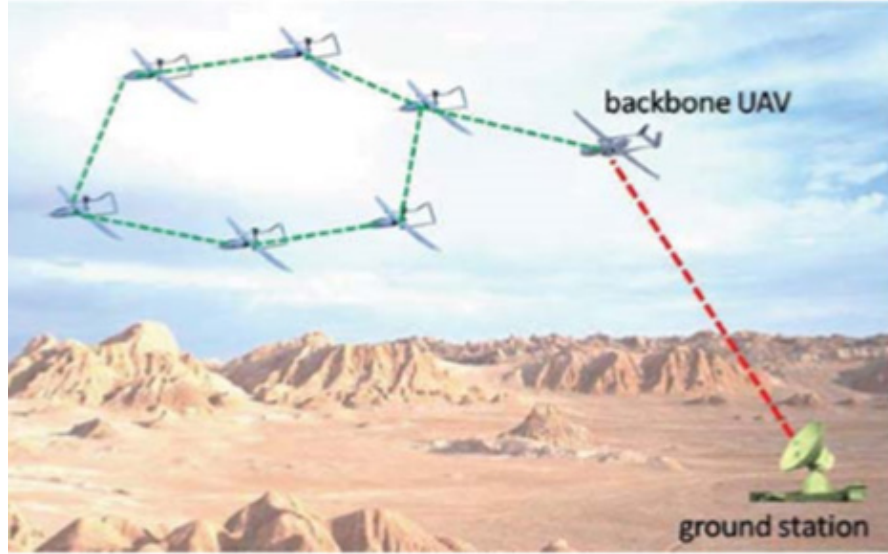


Figure 4. Decentralized UAV Network Architecture. Source: Li, Zhou, and Lamont (2013).

G. LAYER 4 IN UAV NETWORKING: TRANSPORT LAYER

While Layer 3 allows the researcher to set the network routing protocol to maintain the trajectory of packet flow among the nodes through OFDM and MIMO protocol, Layer 4 allows the researcher to test the connectivity between nodes by verifying, through the use of the Hyper Text Transfer Protocol (HTTP), the TCP segment sent and the response between these nodes. As West et al. note (2016), “Before TCP transmits data, it ensures that a connection or session is established, similar to making sure someone is listening on the other end of a phone call before you start talking” (p. 108). By providing that service, TCP enables the user to track the packet delivery from source to destination, to control the transmission on various nodes of the UAV network in free space. Moreover, Layer 4 relies on using the Three-Handshakes method that verifies the response between source and destination by examining the checksum. As West et al. note (2016), “If the two checksums fail to match, the designation host asks the source to transmit the data” (p. 108). This indicates that if packet loss occurs, the checksum is reminding the source to transfer data to verify that the complete data packet has reached its designation. TCP not only provides checksum to confirm data integrity, but also it provides sequence numbering for each segment to enable tracking of each segment and when it arrives.

H. LAYER 7 IN UAV NETWORKING: APPLICATION

While Layer 4 provides test connectivity among nodes, Layer 7 focuses on measuring network performance through software applications such as simulation and other network performance software. The following sections describe the functional model and performance management, in particular. Evaluating network performance involves important metrics to determine node-to-node communication, fault configuration, packet delay, and other constraints in a network that affect its performance. All of these metrics are essential to assessing which architecture can minimize latency. To perform this evaluation, this research uses the functional model, which consists of five components: configuration management, fault management, performance management, security management, and accounting management (Subramanian, 2011). This research performs baseline configuration management, but focuses on performance management because it is the tool used to measure latency, particularly wireless local area network (WLAN) latency, including throughput and delay.

Performance management is used to analyze the health of a mesh network through the observation of traffic issues, status of nodes, and strength of signal to control the stability of the network status. According to Subramanian (2011), “performance management is really (data) traffic management.” (p. 409). In short, performance management of a network focuses on traffic flow (b/s) to monitor the flow of information between various nodes within a mesh network.

Controlling and managing the system by using a network monitoring system will meet all the needs of a network manager to control network elements and maintain the connectivity of network. This, in turn, provides the real-time capture of nodes’ status, traffic, and delay between the ground station and nodes. Therefore, by using network performance data from a network monitoring system, a network manager can track mesh network efficiency and maintain the response time in the network, which enables the network manager to make decisions promptly to sustain network performance and minimize latency.

Performance management encompasses several important factors, including performance metrics and performance statistics, to monitor the mesh network.

1. Performance Metrics

This parameter measures the important factors related to the performance of networks: throughput, response time, network availability, and network reliability. While all these factors are important, this section focuses on network throughput and response time, in particular, which are used to measure latency.

a. Network Throughput

There are several performance metrics to measure the efficiency of a network. One of the most important metrics is network throughput. According to Subramanian (2011), “network throughput are **bandwidth** or capacity of the transmission media, its utilization, and error rate of the channel, peak load, and average load of the traffic” (p. 409). Constraints in free space limit the efficiency of a network, which reduces the flow of information and creates latency between nodes and the ground station in mesh networks.

b. Response Time

Response time measures how long it will take information to transmit from source to destination and back again, which gives a benchmark by which to measure latency. According to Subramanian (2011), “the response time of a network not only depends on the throughput of the network, but also on the application” (p. 409). In other words, response time depends on various elements in the network such as equipment temperature, protocols, radio capabilities, flight capabilities, routing algorithm protocols, and application configuration. All these factors involved in response time efficiency in a mesh network might reduce the response time interval, which indicates an increase in latency.

2. Performance Statistics

Network performance statistics observed from network software relies on various sensors implemented in the nodes. These statistics help the network manager to identify possible sources of latency. It will be useful to discuss the Wireless Sensor Network (WSN)

specifications to explain the sensor capabilities in a mesh network that provide good performance statistics about nodes.

Relying on WSN features and benefits, the UAVs can exchange data. This benefit of WSNs integrates the communication between UAV nodes and the ground station, which allows UAV nodes to exchange data and send it to the ground station. According to Dan Popescu, Cristian Dragana, Florin Stoican, Loretta Ichim, and Grigore Stamatesc (2018), “the UAV has to pass near all of the sensor heads in order to retrieve information”; “The [sensor built in each UAV node] allows to guarantee the feasibility of the trajectory (in the sense that it respects the dynamics of the UAV) [which] allows various algebraic and geometric guarantees” (Introduction, para. 5). This indicates that the WSN ensures collecting information from nodes and passing it to the ground station. Further, the WSN transmits the UAV position and altitude by utilizing algebraic and geometric capabilities to monitor nodes’ status and assists the network manager in controlling the nodes remotely based on sensor alarms.

3. Network Management

While it is important to measure the performance of nodes within networks, managing the network through applications enhances the command and control of a UAV mesh network. Applications to manage and control networks provide a convenient solution to support and track technical issues remotely, which enhances the network manager’s ability to maintain the health of a network according to the application features available. According to Douglas E. Comer (2009, p. 540) “a manager needs to interact with a specific hardware device, the manager runs an application program that acts as a client, and an application program on the network device acts as server.” Network managers’ authority to access the server (agent) allows them to control information sharing, control bandwidth, track the traffic, and change or modify security parameters and other parameters.

Moreover, the network manager can manage packet delay through the use of the conventional transport protocols. Using conventional protocols means a manager’s packets will be subject to the same conditions as normal traffic. Therefore, in the case of a delay, the network manager will control packet traffic remotely using a network application to

avoid packets being dropped between various nodes within a mesh network. In this research, network management occurs via the simulation software discussed in Chapter III.

While this chapter focused on the network layers relevant to latency, the next chapter, on research methodology, sets the simulation parameters and attributes of nodes to measure latency between nodes and the ground station, which provides the baseline for UAV nodes flying in free space and the virtual mesh network.

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III. RESEARCH METHODOLOGY

This chapter discusses the modeling methodology used in this research to assess the relative latency at different altitudes of a UAV network. This modeling via computer simulation describes an architecture consisting of two UAV nodes and having a MANET topology to establish self-configuration without relying on infrastructure support such as a ground station.

This chapter begins by discussing the capabilities of the UAV used in the simulation, specifically, its maneuvering and radio capabilities. Next, the discussion introduces the Riverbed simulation software. The chapter then describes the first scenario, the MANET plus 3000, including the steps to configure the simulation, and the second scenario, the MANET plus 2000. Results of these simulations are discussed in Chapter IV.

A. UAV SYSTEM CAPABILITIES

Identifying UAV system capabilities is critical to modeling the network realistically. This task assists the network manager to design the UAV network architecture. The UAV selected for this research is a Boeing ScanEagle, which supports the MANET topology and has useful capabilities in a military mission. The set of UAV capabilities described in the following paragraphs include the maneuvering and radio capabilities.

1. Maneuvering Capabilities

Table 2 includes the UAV maneuvering capabilities that will be used in simulation.

Table 2. UAV General Characteristics. Adapted from U.S. Air Force (2007).

UAV Model	Scaneagle
Weight	39.7 lb
Length	3.9ft
Wingspan	10.20 feet
Payload	High Resloution Camera
Speed	55-80mph
Operating Altitude	16,000 ft
Endurance	20 + Hours

As Table 2 shows, the ScanEagle's maneuvering capabilities are determined by characteristics such as its weight, size, maximum speed, and maximum flight time. Including these characteristics in the simulation allows the software to determine simulation duration. Modeling various characteristics, such as flight time set to 20 hours, enables the software to determine the duration of the simulation as less than 20 hours. Therefore, using the maximum flight altitude allows the research to adhere to the limit and obtain realistic results within the values entered into the software. The payload of the ScanEagle includes a high-resolution camera, which enables the UAV to transmit real-time pictures of the ground without affecting the ScanEagle's maneuvering capabilities.

2. Radio Capabilities

Whereas the flight characteristics provide information about the ScanEagle's flight ability in free space, radio capabilities are characterized by transmitter power and transmission speed. These capabilities assist the researcher in determining changes that occur in the mission such as packet latency and obstacles that reduce the signal strength within MANET. Several of the relevant radio capabilities of ScanEagle are classified information. The following math, therefore, is used to determine this research's assumptions about the UAV's radio capabilities, and it relies on telecommunication formulas.

a. Maximum Bit Rate

The max bit rate for video describes the speed of data per second; this calculation is determined by the ScanEagle's assumed camera resolution and standard frame rate of 30 fps, based on black and white camera resolution (960*720 p), 24 bits/pixel, and compressed to MPEG format.

Convert Typical Camera Resolution to bit/sec

Camera Resolution = 960*720p = 691200 pixels / frame * 24 bits / pixel = 16,558,800 bits / frame * 30 fps = 497,664,000 bits / sec

Convert bit/sec to MPEG (Compress File)

(497,664,000 b/s) / 40 MPEG = 12,441,600 bits / sec = 12.4 Mbps

b. Transmitter Power

Transmitter power (Pt), which is the power abilities of the transmitter. This calculation is determined by assumption based on various standard parameters using the Pr (Power receiver) Formula. The minimum received power for 802.11g at 54 Mbps is -82 dBm. The gain of the ground turnstile antenna (Gt) is 0 db. The gain of the aircraft blade (Gr) antenna is 6 db. The distance between the ground antenna and the UAV's is (5 km), and the speed of light (3×10^8) m/s.

$$\begin{aligned} Pr &= Pt + Gt + Gr - Lp \\ (-82\text{dBm}) &= Pt + 0\text{ db} + 6\text{db} - 20\log(4\pi * 5000(\text{m}) * 2.4 \times 10^9 / 3 \times 10^8) \\ 26\text{dBm} &= Pt \end{aligned}$$

For simulation purposes, it is necessary to convert dBm to watts.

$$\begin{aligned} &\text{Convert (26 dBm to watts)} \\ 10^{(26\text{ dBm} / 10)} &= 400\text{ mW} = 0.4\text{ W} \end{aligned}$$

Table 3 shows the assumptions about ScanEagle radio capabilities.

Table 3. UAV Radio Capabilities.

Max.Bitrate of Video	12.4 Mbps
Max Transmission Distance	2.4GHz: 4.3 miles (5 km, FCC)
Operating Frequency	2.4GHz
Transmitter Power	2.4GHz: ≤ 26 dBm (0.4 watts)

B. RIVERBED SIMULATION SOFTWARE

Utilizing Riverbed Modeler Academic Edition software enables the researcher to create a baseline model to analyze MANET latency between UAV nodes and the ground station. This simulation allows a network manager to configure various nodes, and facilitate communication by using multiple protocols to establish communication. Riverbed allows the researcher to configure protocols between UAVs; control distance between nodes; set up initial waiting time; adjust pitch, yaw, roll (height and movement) of the UAVs; and test the signal throughput and packet latency. This in turn allows the network manager to analyze various network scenarios and assists in simulating potential options. Therefore, this research explores 3,000 feet and 2,000 feet options, which are the lowest possible altitudes at which the UAVs can avoid enemy weapons. It is also important to model network performance capabilities that enable transmitting better video quality to ground stations.

C. SCENARIO 1: MANET PLUS 3000

The purpose of Scenario 1 testing and simulation is to measure direct path and latency between the sender (the ground control station) and receivers (UAV nodes). In this scenario, two UAVs operate at 3,000 feet (approximately 1 km) above the ground control station (GCS), moving at a constant speed of 10 m/s and keeping a constant position relative to each other at approximately 5 km from the GCS and approximately 7 km from UAV 1 to UAV2. Therefore, the initial pitch is set as autocomputed to track the UAVs' position and altitude. Likewise, the initial yaw and roll are set to autocomputed to control

the UAVs and ensure that the direction (left or right) is tracked during the flight. Providing that scenario setup as the baseline for the simulation experiment allows the researcher to visualize the UAVs' link status, throughput, and packet delay at specific initial altitude through reports and statistics. Based on these results the researcher is able to identify maximum performance in the network design to serve as benchmark as constraints are included in the next scenarios.

The following section shows the setup for Scenario 1 in Riverbed.

1. UAV Configuration

In this step, conducting the configuration for each UAV's nodes and the GCS allows the researcher to identify the status of nodes using the ping command in the event of network failure. This step is repeated in nodes using the following pattern shown in Table 4.

Table 4. UAV Nodes' Internet Protocol Addresses.

Host Name	IP
Ground Station	192.168.1.1
ScanEagle-1	192.168.1.2
ScanEagle-2	192.168.1.3

These internet protocol (IP) addresses are assigned in Riverbed by editing the attributes of each node, as shown in Figure 5.

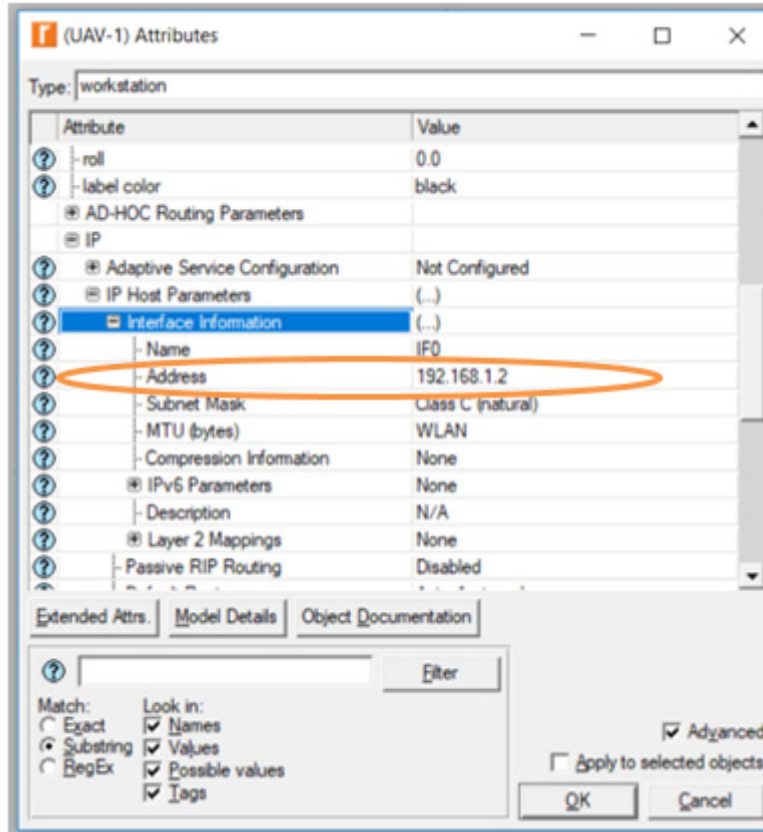


Figure 5. UAV IP Setup in Riverbed.

It is also important after setup of the IP address to enable the routing information protocol (RIP) for all nodes, to establish the hop count between various nodes within MANET. Figure 6 shows the RIP setup.

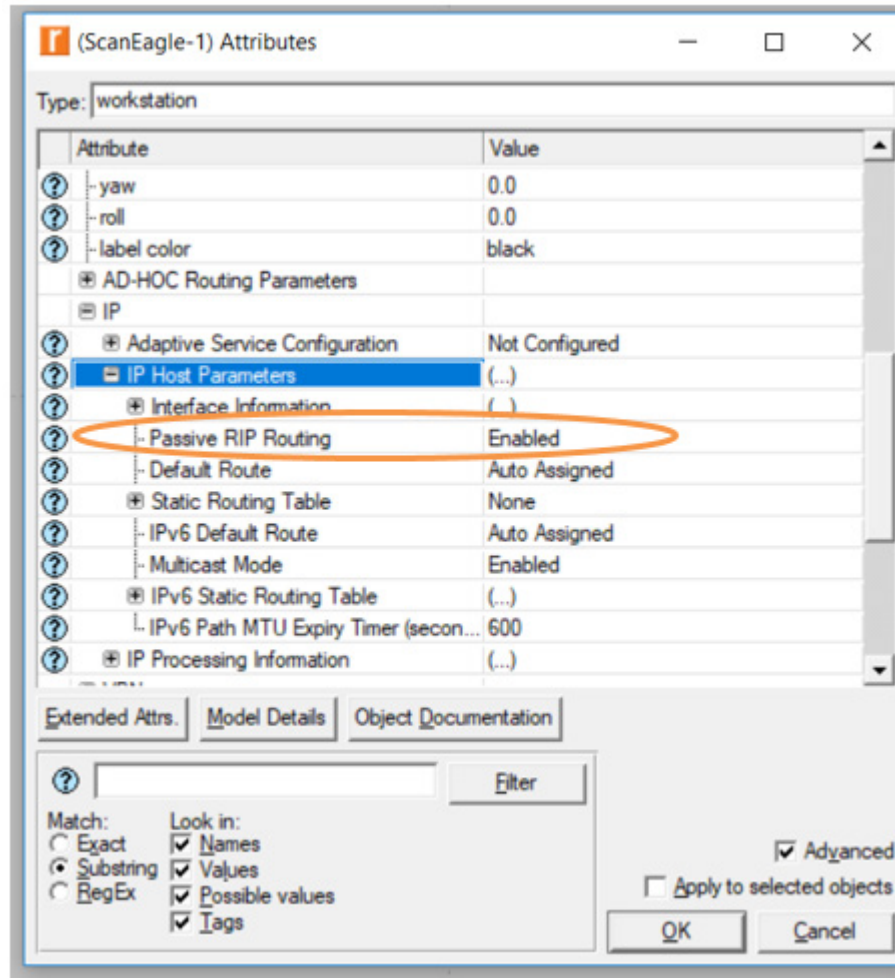


Figure 6. RIP Setup in Riverbed.

2. IP Forwarding Setup

After assigning each node's IP address and enabling the RIP, the researcher must enable the IP forwarding to determine which packet can be sent to neighbor nodes. This process allows the packet to be transmitted along a different route in an ad-hoc network. Figure 7 shows the status option of the IP forwarding table.

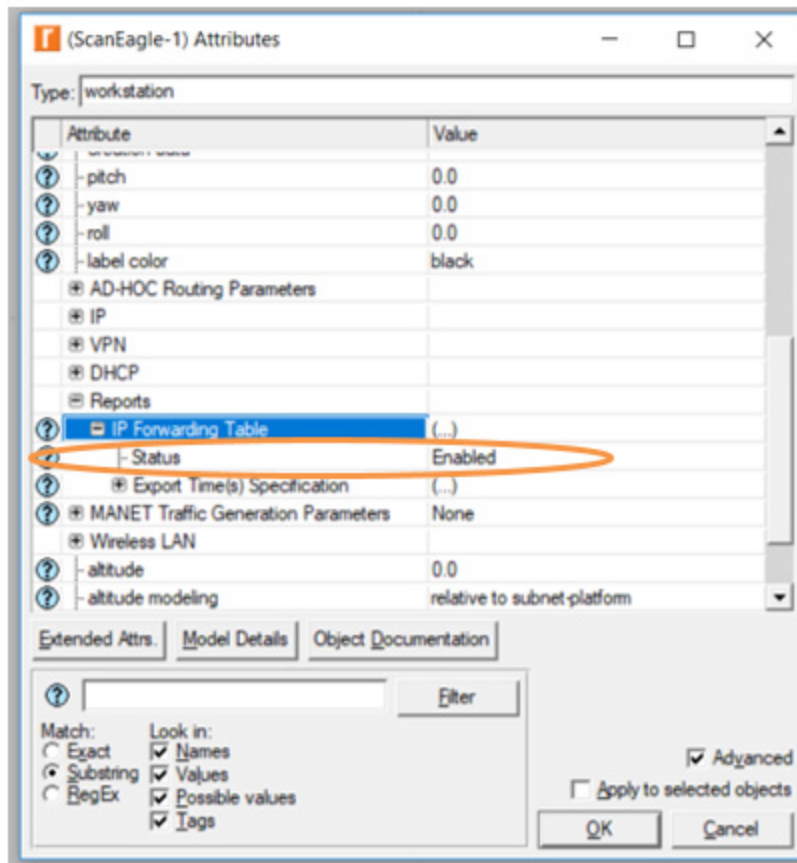


Figure 7. Enable IP Forwarding Table in Riverbed.

3. UAV Radio Protocols Setup

In this step, the researcher sets up the radio protocols between the GCS and the UAV nodes within MANET. The nodes are configured to use 802.11n at 2.4 GHz and 65Mbps. This configuration maintains high throughput and allows the UAV nodes to operate up to 5 km from the GCS. Figure 8 shows the configuration of radio protocols in Riverbed.

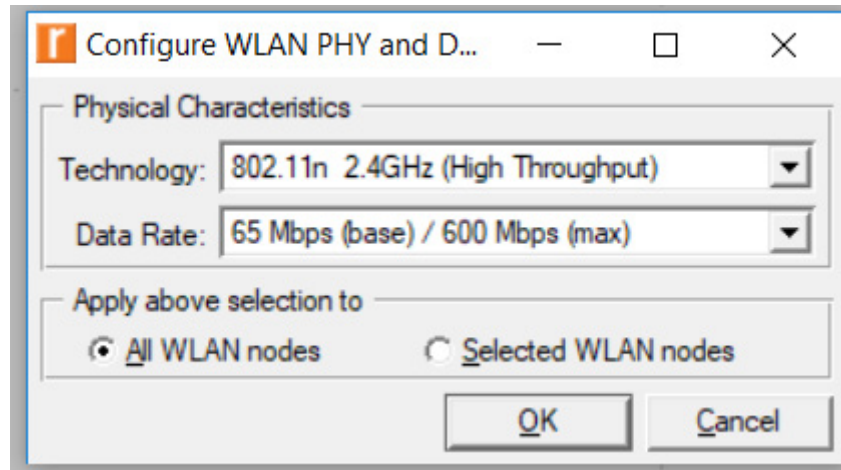


Figure 8. UAV Protocol Setup in Riverbed.

4. UAV Ad-Hoc Parameters Setup

After setting up the UAVs' radio protocols, the researcher sets up the ad-hoc parameters to initiate routing protocols between the GCS and the nodes. In this setup, the researcher utilizes DSR protocols that allow the nodes to be self-configuring and self-organizing. Consequently, when a path failure occurs, the DSR will identify another path. Figure 9 shows the ad-hoc parameters setup. The DSR record route and the DSR record export should be enabled.

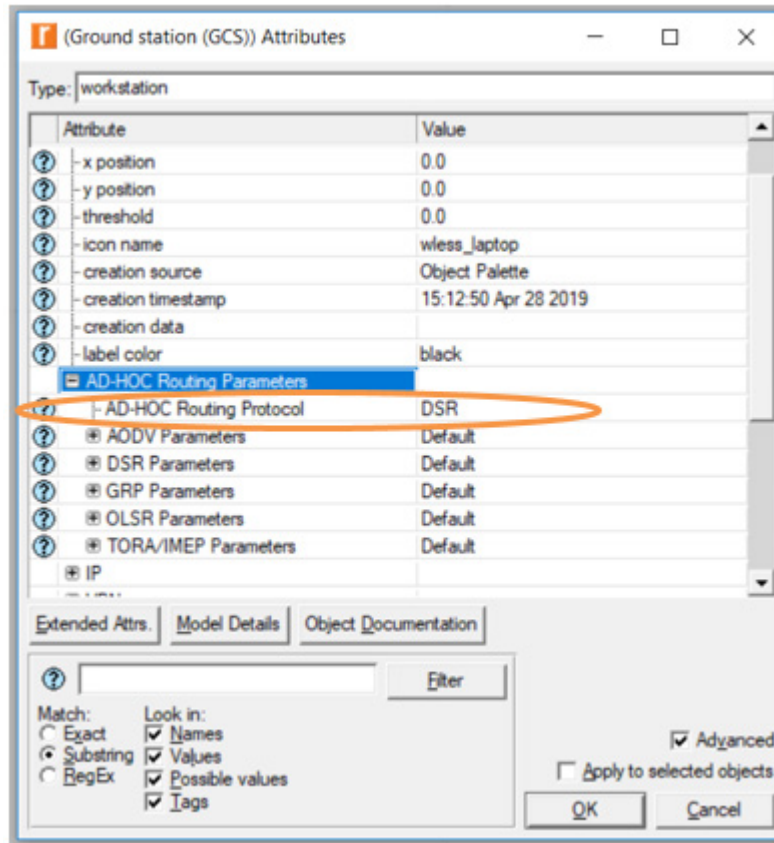


Figure 9. Ad-Hoc Routing Parameters Setup in Riverbed.

5. UAV Geographic Location

At this point it is useful to state the assumption of this research that this maneuver was conducted at Camp Roberts on an area approximately 7 Km. Therefore, the forthcoming setup—define trajectory, altitude level, and distance—depend on this area of operation. Figure 10 shows the geographic location for Camp Roberts Army Base located in California.



Map obtained from Google Earth, retrieved July 31, 2019, from <https://earth.google.com/web/@36.5182785,-121.9521154,18.55555598a,829.12405936d,35y,0h,0t,0r>.

Figure 10. UAV Maneuver Geographic Location (Camp Roberts, CA).

6. UAV Position Setup

Based on the geographic location for the UAV maneuver, the researcher sets UAV positions using the Pythagorean Theorem: $z^2 = x^2 + y^2$, where z is the actual distance between the GCS and each UAV, x is the horizontal distance between the GCS and each node, and y is the vertical distance between the GCS and each node. Therefore, to calculate distance, the researcher must use Pythagorean theory $z = \sqrt{x^2 + y^2}$. The ground station coordinates are assumed as (0,0), ScanEagle 1's coordinates as (3.53,3.53), and ScanEagle 2's as (-3.53,3.53); and the distance between the GCS and each UAV is assumed to be approximately 5 Km. Figure 11 shows changes made to position by relying on Pythagorean theory and software characteristics in inserting attributes.

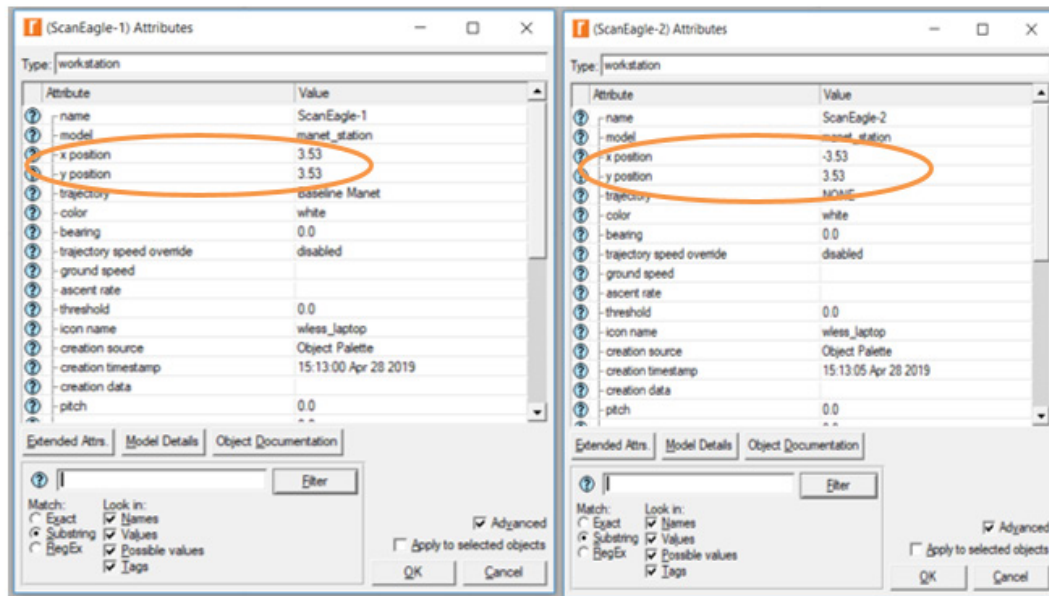


Figure 11. ScanEagle1 and ScanEagle2 Positions in Riverbed.

7. UAV's Altitude Setup

The next step is adjusting the altitude for the UAVs' nodes to obtain accurate measurement of the UAV altitude level in free space. This modification allows the software to specify UAV position in free space. In both scenarios, pitch, yaw, and roll are kept to autocomputed to track UAV position and movement during maneuver and to establish baseline network performance. Figure 12 shows the parameters for defining trajectory to adjust altitude and position level for all UAVs during maneuver.

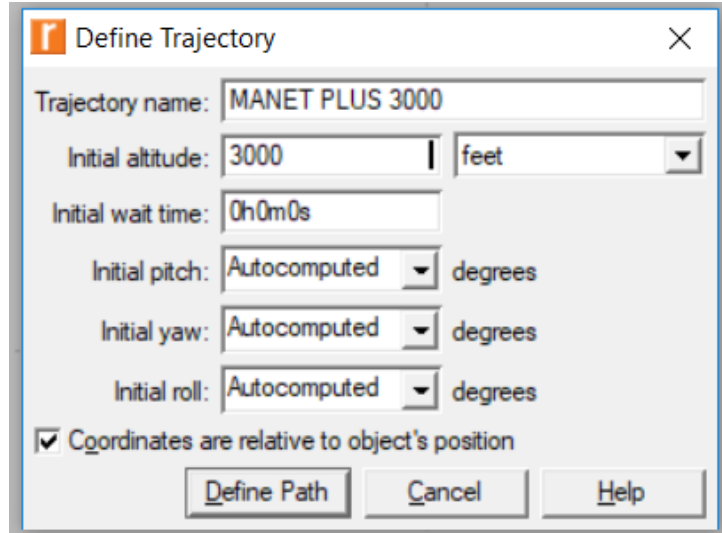


Figure 12. UAV Altitude Setup in Riverbed.

8. UAV Trajectory Setup

Once the UAVs' positions are defined, the researcher defines the trajectory of the UAV nodes with consideration that the GCS is at 0 level. This trajectory specifies the path of both UAVs during maneuver. This also indicates that the trajectory of these nodes maintains the antenna orientation at the same level. Figure 13 shows the UAVs' trajectory setup in Riverbed software.

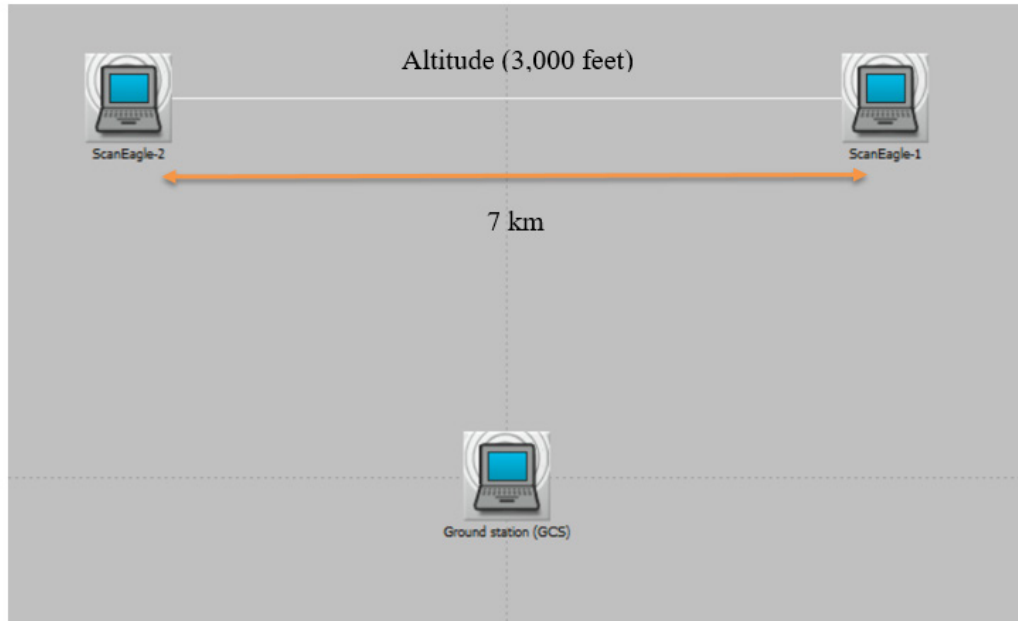


Figure 13. UAV Trajectory Setup in Riverbed.

9. UAV Data Table

After all settings are input into the software, it produces the UAVs' trajectory table. This allows the researcher to verify that all input is accurate and the distance between UAVs is within the range of radio capabilities, and the altitude and speed of both UAVs are identical. Figure 14 summarizes the setup for implementing the simulation of MANET baseline latency. This information in the trajectory table shown is based on (10 m/s) trajectory speed.

The screenshot shows a software window titled "Edit Trajectory Information". It contains a table with two rows of trajectory data. Below the table are several configuration options and buttons.

	X Pos (km)	Y Pos (km)	Distance (km)	Altitude (ft)	Traverse Time	Ground Speed	Ascent Rate (ft/sec)	Wait Time	Accum Time	Pitch (degrees)	Yaw (degrees)	Roll (degrees)
1	0.000000	0.000000	n/a	3,000.000	n/a	n/a	n/a	0	00.00s	Autocomputed	Autocomputed	Autocomputed
2	-7.002653	0.000000	7.0027	3,000.000	11m40.27s	22.3692	0	0	11m40.27s	Autocomputed	Autocomputed	Autocomputed

Below the table, there are several controls:

- ☒ Coordinates are relative to object's position
- Execute trajectory: times
- ☐ Traverse trajectory backward with wait time of seconds before execution
- Ground speed in:
- Distance in:
- Altitude in:
- Buttons: Insert, Delete, Redefine..., Import STK .e..., OK, Cancel

Figure 14. UAV Trajectory Data Table in Riverbed.

10. UAV Traffic Flow Setup

Once the physical configuration of the nodes is complete, the next step is establishing traffic flow. This setup assists researchers to identify and examine the total bit flow per second, which is needed to observe the network health status between UAV nodes and the GCS. In this task the researcher must set up the TCP, which is operates in Layer 4 (Transport layer) to check the connectivity of devices and examine the response between multiple sources and their destination. Testing and examining connectivity in the baseline MANET scenarios between multiple inputs and outputs captures the speed of data flow from the GCS to all other nodes in the MANET. The first step is to set up the IP unicast traffic flow to generate the traffic center report, followed by setting up VOIP to simulate audio and video transmission.

a. Create IP Uicast Traffic Flow

In this setup, the researcher creates IP unicast traffic (full mesh among all nodes) to verify the throughput among all nodes within the MANET. In this step, the researcher selects Auto Assigned for the destination IP address, and to support streaming multimedia, for type of service AF41 is selected. Finally, to obtain good throughput for the purpose of

UAV video transmission in capturing ground images, the researcher enters 100000 packet/s and 63 Mbps. Figure 15 shows the IP unicast traffic flow parameters set up in Riverbed.

Create IP Unicast Traffic Flows

Node selection

- ☒ Full mesh between all nodes
- ☐ To all other nodes from: Ground Station
- ☐ From all other nodes to: Ground Station

Intensity

Packets/sec: 100000

Bits/sec: 63000000

Duration (secs): 3600

Characteristics

Description: Represents IP Unicast Traffic Flows

Color:

☒ Set start time 12:07:00.000 Aug 14 2019

☐ Characterize demands

Socket information

Destination IP address: Auto Assigned Source port: http

Type of service: AF41 Destination port: http

Protocol: TCP

Create Cancel

Figure 15. IP Unicast Traffic Flow Setup in Riverbed.

b. Create VOIP Traffic Flows

After setting up the IP unicast traffic flow, the researcher sets up the Voice over IP (VOIP) by using type of service (Streaming Multimedia [AF41]), to ensure that all delivery of multimedia and communication over IP is implemented between the GCS and other nodes. Figure 16 shows the setup of VOIP in Riverbed.

Create VoIP Traffic Flows

Node selection

- ☒ Full mesh between selected nodes
- ☐ To other selected nodes from: Ground station (GCS)
- ☐ From other selected nodes to: Ground station (GCS)
- ☐ Include only VoIP gateways as source and destination nodes

Traffic Details

Call volume: 1000 Units: Erlangs

Average call duration: 300 seconds/call

Voice flow duration: 3600 seconds

Encoder scheme: G.711

Type of service: AF41

☒ Set start time 15:25:35.000 Aug 08 2019

☒ Include overhead (bytes) RTP/UDP/IP

Advanced Options... Create Cancel

Figure 16. VOIP Traffic Flow Setup in Riverbed.

c. Analyze the Traffic Center Report

Based on the completed setup, the software produces the traffic center report, which allows the researcher to visualize the total bits per second to identify the throughput efficiency from the traffic center. Figure 17 is an example of the traffic center report for this scenario. Results are discussed in Chapter IV.

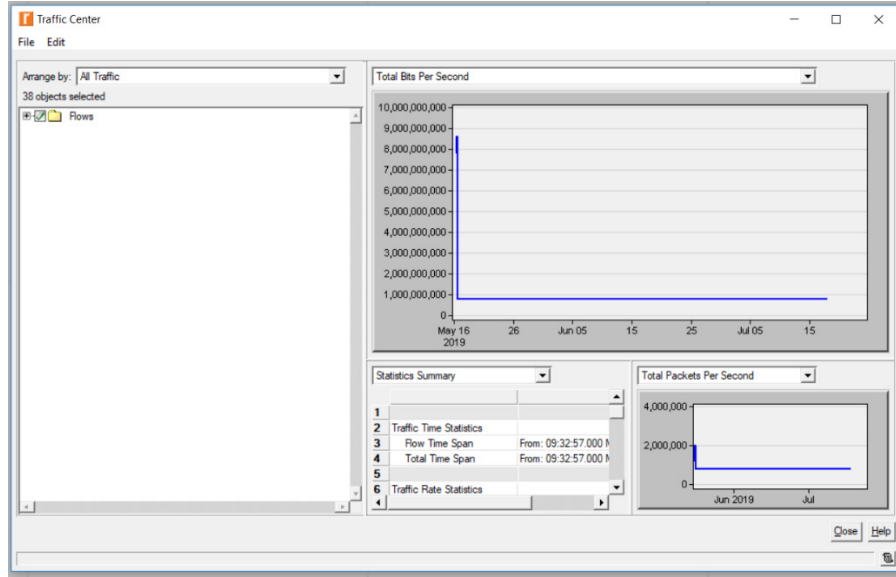


Figure 17. Traffic Center Report Generated by Riverbed.

11. MANET Traffic Generation Setup

After traffic flow setup, it is important to specify the packet size and destination. In this research, the destination of one of the UAV nodes is set to other node's destination. Packet size should be higher than the Intensity parameters bps field / Packet/sec field, which increases the traffic sent and received within the MANET. Table 5 shows the distribution of MANET traffic destinations built in each node to ensure the traffic path and data transmission to all nodes in the mesh network.

Table 5. Distrbution of MANET Traffic Destinations.

UAV's IP	Destination
192.168.1.1	Nodes: 192.168.1.2 / Nodes: 192.168.1.3
192.168.1.2	Nodes : 192.168.1.1 / Nodes: 192.168.1.3
192.168.1.3	Nodes : 192.168.1.1 / Nodes: 192.168.1.2

Figure 18 shows the ground station distribution of MANET traffic generation, which must be configured in other nodes to ensure data transmission.

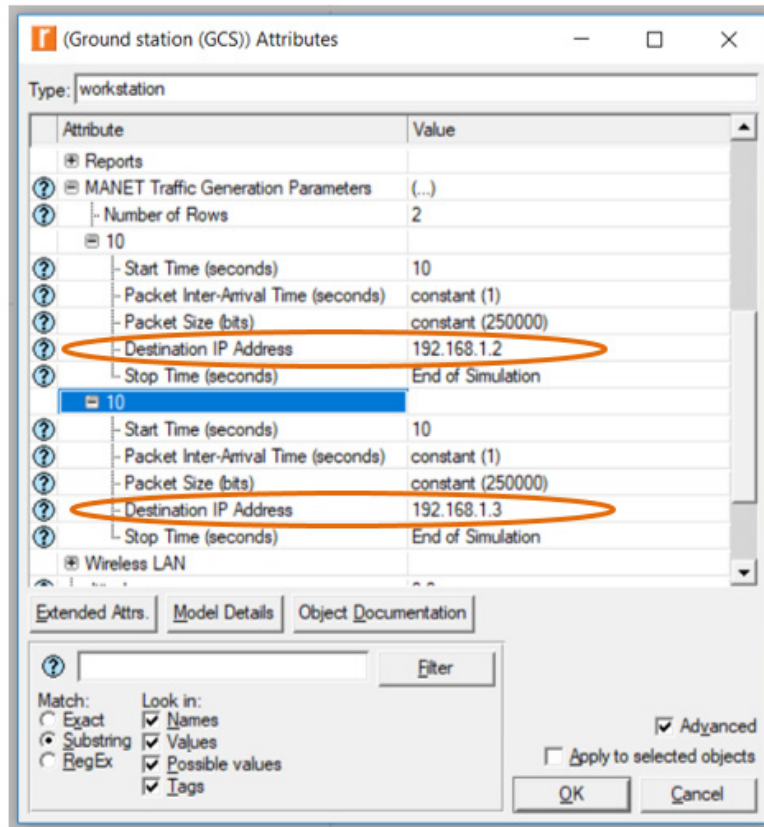


Figure 18. MANET Traffic Generation Parameters in Riverbed.

12. Descriptive Statistics

Finally, the researcher must select the appropriate statistics report to obtain the results. The researcher selects the MANET report to visualize the latency occurring between the GCS and UAV nodes. Figure 19 shows the statistics selection option.

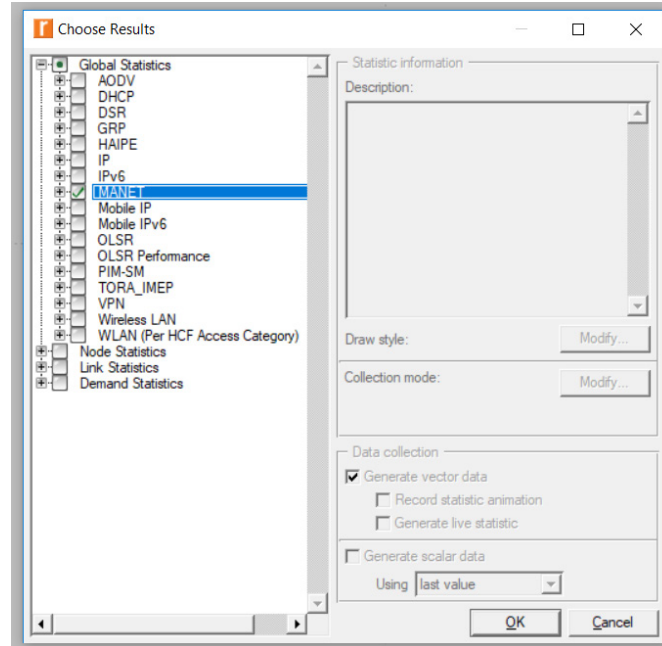


Figure 19. MANET Descriptive Statistics Report Selection in Riverbed.

13. Run Simulation

After verifying the parameters, in this step the researcher runs the hour-long simulation and selects the report to view latency in the MANET as shown in Figure 20. The MANET latency report supports the researcher's effort to analyze packet latency during this simulation. The measurement used to determine MANET latency in this research is the MANET delay report, which captures the link state efficiency between the GCS and the UAVs in free space, including orientation, altitude, distance, and speed. It is also important in this step to change the parameters of the Link Usage report to peak usage for all links to obtain link patterns showing the signal throughput status.

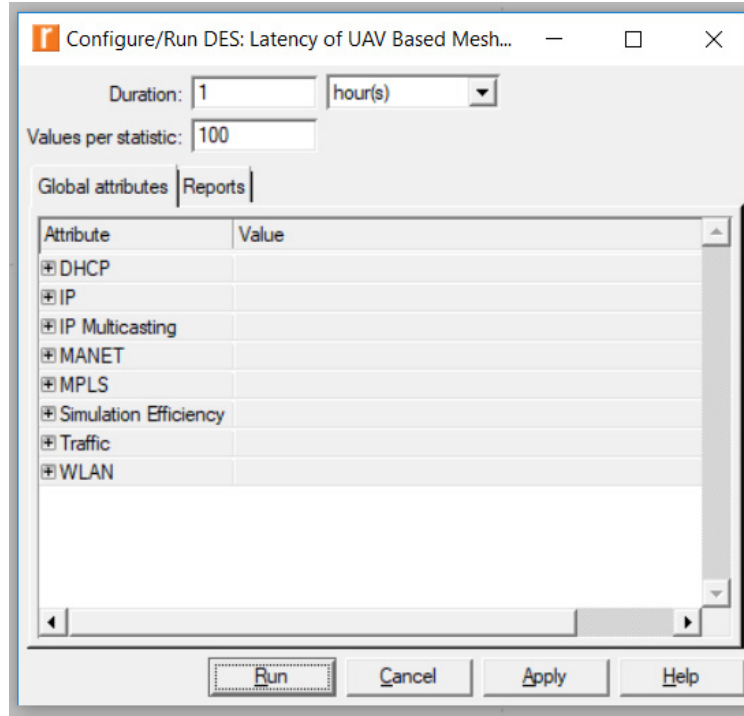


Figure 20. Simulation Report Window in Riverbed.

D. SCENARIO 2: MANET PLUS 2000

In this scenario, the researcher adjusts UAV position altitude to 2,000 feet to observe any difference in MANET latency. The nodes are approximately 0.609 km above the ground station as compared to Scenario 1 in which they were 1 km above the GCS. This change in parameters of altitude is intended to enhance energy replenishment and achieve the objective of maintaining the energy level among UAVs in the MANET, which does not rely on fixed infrastructure. According to Yong Zeng, Rui Zhang, and Teng Joon Lim (2016), “[The] UAV is scheduled to leave the serving area for energy replenishment, during which the service gap is temporarily filled by neighboring UAVs via e.g., increasing the transmission power and/or adjusting the aircraft positions. (p.39). This indicates that adjusting the altitude between the GCS and UAVs is the solution to reduce energy consumption during the UAV mission and obtain energy efficiency between UAV nodes. Changing the distance reinforces UAV telecommunication because every maneuver requires energy consumption. Therefore, controlling the energy will not only control the real-time flight interval, but also reduce energy consumption, which will enhance overall

energy efficiency (bits/Joule). Enhancing energy efficiency, in turn, leaves more power to transmit data, which could reduce latency.

In this option, therefore, the two UAVs will operate at 2,000 feet above ground level. Both UAVs are moving at a constant speed of 10 m/s, and maintain a constant position relative to each other. The initial pitch is set as autocomputed to keep the UAVs at the same altitude. Likewise, the initial yaw and roll are set to autocomputed to control the UAVs and ensure that the direction (left or right) is tracked during the flight. Based on these settings, the researcher reruns the simulation to identify the difference in latency between this scenario and Scenario 1 (3000 PLUS MANET). The parameter changes for Scenario 2 are the UAVs' altitude setup and the UAVs' trajectory setup. Unless noted otherwise, all other simulation parameters are the same as in Scenario 1.

1. UAV Altitude Setup

Based on assumptions of Scenario 1, changing the UAVs' altitude to set up all UAV nodes involved in this simulation will maintain UAV altitude. This change of altitude changes the distance between nodes and the GCS in the MANET, which might produce different results from those of Scenario 1. Figure 21 shows the changes entered for this option.

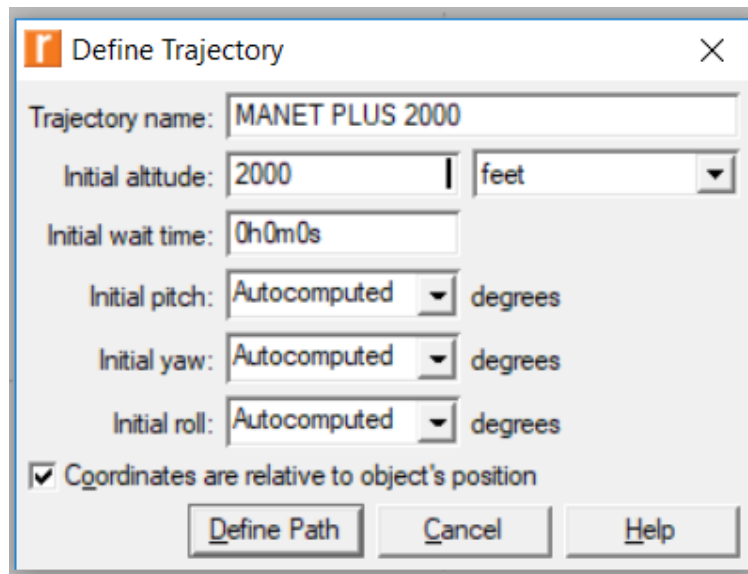


Figure 21. UAV Altitude Setup in Riverbed.

2. UAV Trajectory Setup

After setting up the altitude between the nodes and GCS, the researcher must specify the trajectory path and establish a link between the two UAV nodes. Figure 22 shows the UAVs' trajectory setup.

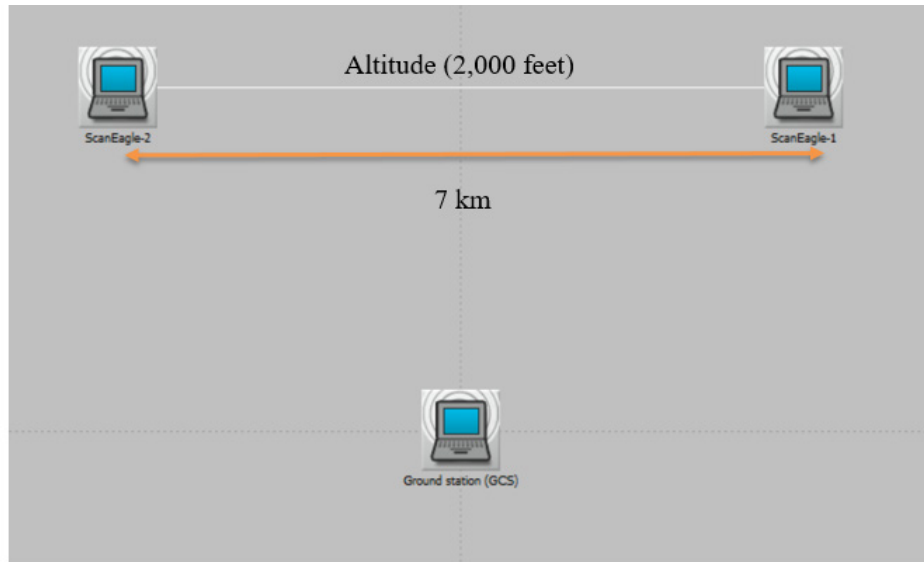


Figure 22. UAV Trajectory Setup in Riverbed.

3. UAV Data Table

Figure 23 shows the table containing the changed altitude and distance between UAVs, which is used to verify that the setup is accurate. This parameter is set at 10 m/s for speed as it was for the MANET Plus 3000 UAV nodes' speed.

The screenshot shows a software window titled "Edit Trajectory Information". Inside, there is a table with 13 columns: X Pos (km), Y Pos (km), Distance (km), Altitude (ft), Traverse Time, Ground Speed, Ascent Rate (ft/sec), Wait Time, Accum Time, Pitch (degrees), Yaw (degrees), and Roll (degrees). The table contains two rows of data. Below the table, there are several controls: a checkbox for "Coordinates are relative to object's position" (checked), a field for "Execute trajectory" (set to 1) times, a checkbox for "Traverse trajectory backward with wait time of" (unchecked) with a value of 0.000000 seconds, and three dropdown menus for "Ground speed in:" (mi/hr), "Distance in:" (kilometers), and "Altitude in:" (feet). At the bottom are buttons for "Insert", "Delete", "Redefine...", "Import STK.e...", "OK", and "Cancel".

	X Pos (km)	Y Pos (km)	Distance (km)	Altitude (ft)	Traverse Time	Ground Speed	Ascent Rate (ft/sec)	Wait Time	Accum Time	Pitch (degrees)	Yaw (degrees)	Roll (degrees)
1	0.000000	0.000000	n/a	2,000.000	n/a	n/a	n/a	0	00.00s	Autocomputed	Autocomputed	Autocomputed
2	-7.002653	0.000000	7.0027	2,000.000	11m40.27s	22.3692	0	0	11m40.27s	Autocomputed	Autocomputed	Autocomputed

Figure 23. UAV Data Table in Riverbed.

The results from these scenarios are discussed in Chapter IV.

E. SUMMARY OF MANET MODELING AT ALTITUDES OF 3000 FEET AND 2000 FEET

Table 6 summarizes all changes made in the MANET model from Scenario 1 (MANET PLUS 3000) to Scenario 2 (MANET PLUS 2000). This table summarizes the comprehensive approach and methodology the researcher used to run the simulations and obtain the results, which provides a baseline for creating a MANET architecture that analyzes latency between the GCS and UAV nodes.

Table 6. Summary of Developed MANET Model.

Summary of MANET Model Parameters		
1	Environment Area (m X m)	10*10
2	Routing Protocols	DSR
3	Data Rate	65 Mbps / 600 Mbps max speed (2.4GHZ high Throughput)
4	Traffic Source (Bytes)	HTTP
5	Network Size (No.of nodes)	3
6	Mobility speed	10 m/s
7	Simulation Time (seconds)	3600
8	MAC protocol /physical	802.11/n
9	Transmission Power	0.4 W (400 mW)
10	Node Placement	Ground station Level 0 / SscanEagle 1 [3.5,3.5]/Scaneagle 2 [-3.5,3.5]
11	Antenna of Nodes	Omnidirectional Antenna (Assumption)
12	Altitude (Trajectory)	Scenario 1 [3000 feet] , Scenario 2 [2000 feet] Inensity [packet/sec :100,000 , bits/sec:63Mbps]
13	Traffic Flow	IP unicast (Full mesh network) [TCP/HTTP /Type of service :Multimedia Streaming (AF41)]
14	MANET Traffic Generation	All Nodes [Packet size (constant :250,000 bits/sec),Destignation (see chapter 3 p.44-45)
15	VOIP	Full Mesh network [Duration :3600 Sees]
16	IP Forwarding	All Nodes [Select Enable]
17	RIP	All Nodes [Select Enable]
18	Simulation Report Statistics (DES)	MANET (Delay Report)
19	DSR Record Route	Enable
20	DSR Record Export	Enable
21	Link Usage Report	Peak Usage for All Links
22	Traffic Sent	See Result in chapter 4
23	Traffic Received	See Result in chapter 4
24	Delay	See Result in chapter 4

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IV. SIMULATION RESULTS

Based on the methodology applied in the previous chapter, this chapter presents the results and findings of the simulation. First, it discusses the results presented in the DSR MANET Delay Reports from the two scenarios. It then determines the differences between these scenarios. The simulation results indicate that there is no significant difference in MANET delay (bits per second) between Scenario 1 (MANET PLUS 3000) and Scenario 2 (MANET PLUS 2000).

A. SCENARIO 1: DSR MANET DELAY REPORT (PLUS 3000) RESULTS AND DISCUSSION

In this section the researcher focuses on MANET delay and throughput (traffic sent and traffic received) output results based on UAVs positioned at an altitude of 3,000 feet.

The graphs in Figure 24 show the descriptive statistics for MANET delay based on the DSR routing algorithm, network size of three nodes, and mobility speed of 10 m/s. In this case, one node is the GCS and two nodes behave as MANET stations (mobile nodes) within 7 km distance between ScanEagle 1 and ScanEagle 2, operating at 3,000 feet above the GCS .

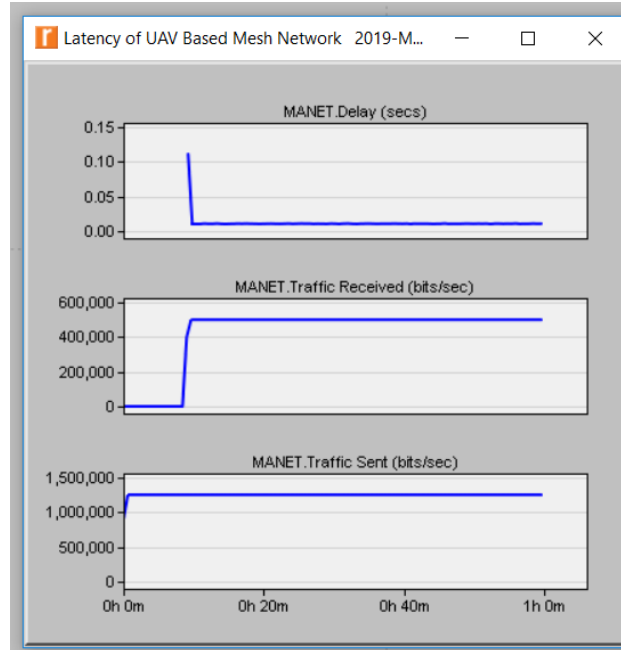


Figure 24. MANET Plus 3000 Results in Riverbed.

The results indicate that MANET traffic sent and MANET traffic received can affect the delay of the network in various degrees. The IP unicast parameters were changed by sending 100,000 packets per second, while traffic flow speed was set as 63 Mbps. For MANET traffic generation with the packet size of 250,000 bits, the delay is 0.11 seconds and the throughput of the sent traffic is approximately 1,250,000 bits per second, while the throughput of the received traffic is approximately 500,000 bits per second. According to the mobility MAC protocol/physical (802.11), routing protocols (DSR), size of network, mobility speed (10 m/s), and altitude (3,000 feet), with 7 km distance between the UAVs' nodes, the mobility delay is significant for a mission in this area based on the MANET delay report generated.

B. SCENARIO 2: DSR MANET DELAY REPORT (PLUS 2000) RESULTS AND DISCUSSION

In this section the researcher focuses on MANET delay and throughput (traffic sent and traffic received) output results based on the UAVs' position at an altitude of 2,000 feet.

The graph in Figure 25 shows the descriptive statistics for MANET delay based on the DSR routing algorithm, a network size of three nodes, and mobility speed of 10 m/s. In this case, one node is the GCS and two nodes behave as MANET stations (mobile nodes) within 7 km distance between ScanEagle 1 and ScanEagle 2, operating at 2,000 feet above the GCS .

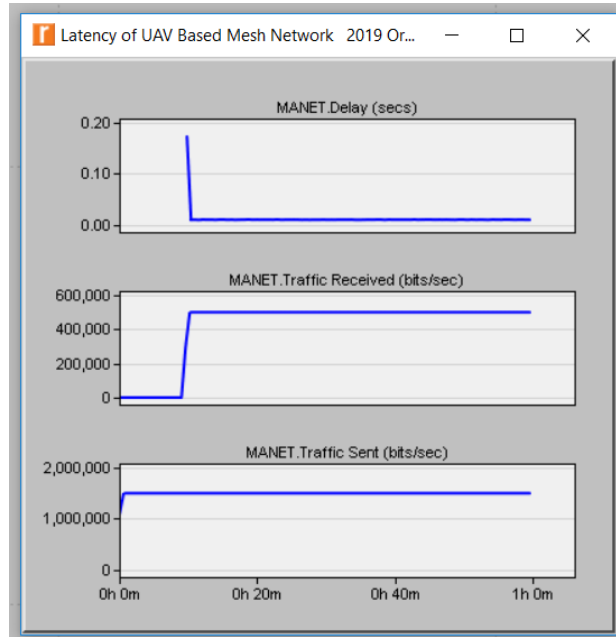


Figure 25. MANET Plus 2000 Results in Riverbed.

Based on this case, the IP unicast parameters were changed to send 100,000 packets per second, and traffic flow speed was set as 63 Mbps. For MANET traffic generation with a packet size of 250,000 bits, the delay is approximately 0.17 seconds and the throughput of sent traffic is approximately 1,500,000 bits per second, while the throughput of received traffic is approximately 500,000 bits per second. Given the mobility MAC protocol/physical (802.11), routing protocols (DSR), size of network, mobility speed of 10 m/s, altitude of 2,000 feet and 7 km distance between UAV nodes, the mobility delay is significant for a mission in this area based on the MANET delay report generated.

C. RESULTS COMPARISON

The results from both scenarios reveal that there is no significant difference in latency in the MANET between when the UAVs operated at an altitude of 3,000 feet and 2,000 feet, respectively, when the same parameters used in this research were used in the Riverbed simulation (OPNET). Therefore, in a similar mission, using the altitude of 3,000 feet would be desirable from the standpoint of safety, video surveillance, and network performance.

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis has built upon research into human and organizational factors in networking. By measuring wireless delay through simulation of UAV MANET networks with constant pitch, yaw, and roll at different altitudes, it aims to enhance C2 and network management, which can reinforce the information cycle in the military operation environment. This chapter discusses lessons learned during the simulations, summarizes the results, and offers conclusions based on the results. This chapter also makes recommendations for future research.

A. METHODOLOGY: LESSONS LEARNED

During this research, the researcher learned several lessons about configuring the simulation:

- In MANET traffic generation setup, configuring each node with the other nodes requires, generating sent and received traffic which results in finding the delay between those nodes.
- In MANET traffic generation setup, the network manager must first determine the packet size by measuring intensity (the bps field divided by packet/sec) to specify the appropriate packet size to radio capabilities bps.
- In traffic flow setup, it necessary to use unicast traffic flow rather than multicast because unicast relies on the three-handshake method of telecommunication between nodes to verify traffic between each pair of nodes.

B. SUMMARY AND CONCLUSION

Based on the UAV simulation results using MANET, Scenario 1 (MANET Plus 3000) displays no more delay than Scenario 2 (MANET Plus 2000). Further, the results indicate that even an altitude of only 1,000 presents no significant difference in MANET

latency results in comparison to Scenario 1 (MANET Plus 3000) and Scenario 2 (MANET Plus 2000). Higher altitudes, however, are better for practical considerations. As already noted, UAVs can fly at higher altitudes with no significant difference in latency, and an altitude of 3,000 feet in particular allows for observation of a wider area and reduces the UAVs' vulnerability to enemy weapons.

Although the simulation results provide a baseline latency measurement for the two scenarios presented, they do not consider air and equipment temperature or other constraints that might affect MANET latency or change the results obtained in this research. Therefore, to obtain a more realistic MANET latency result, future researchers using Riverbed to model the UAV architecture should include such constraints to the baseline methodology applied in this research. To assist in this process, the appendix contains a template to help in modeling UAV-based MANET latency and throughput.

C. FUTURE RESEARCH

This thesis examines the throughput of the MANET network using a Riverbed simulation model to analyze MANET latency. While this approach does offer useful insight into UAVs and latency in network, other features of the network still require in-depth analysis to improve C2 and network management.

From the network manager's standpoint, using particular network parameters, different protocols, and different numbers of drones; simulating different altitudes; and changing the distance between UAVs and the GCS will be appropriate to obtain better results in testing to fine tune the UAV's architecture and minimize wireless delay. This in-depth examination of multiple scenarios and methodology will assist the network manager to track and respond to the changes that occur when using various variables to finalize the topology and architecture that will be used in real military operations.

From the constraint influence standpoint, in-depth measurements of constraints such as environmental temperature and UAV nodes' temperature can give more accurate results to researcher in measuring the latency in seconds, because of the effect of these constraints in mesh networks. Such constraints will result in creating latency between nodes and the GCS. Adding these constraints will refine the results from this research and

offer the researcher an approximate visualization of what will occur in realistic free space and what is better for safe maneuvering of the UAVs.

These more realistic simulations can serve as a preliminary step before conducting experimentation in the field, and will enhance the network manager's decision making and the command and control cycle.

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APPENDIX. MANET SIMULATION TEMPLATE

File Name: _____

Test No.: _____

Software Used _____

Date _____

MANET Model Parameters

1. Environment Area (m X m) _____

2. Routing Protocols:

☐ DSR

☐ AODV

☐ OLSR

If Using DSR Routing Protocols (Enable Both Parameters Below)

DSR Record Route

☐ Enable

☐ Disable

DSR Record Export

☐ Enable

☐ Disable

3. Data Rate _____

4. Traffic Source

☐ HTTP

☐ FTP

☐ Others _____

5. Network Size (No. of Nodes) _____

6. Mobility Speed _____

7. MAC/ Protocol Physical _____

8. Transmission Power _____
9. Node Placement _____
10. Altitude _____
11. Type of Antenna _____
12. Traffic Flow
☐ IP Unicast ☐ IP Multicast
13. VOIP _____
14. MANET Traffic Generation
Packet Size (bits/sec ÷ Packet /sec) _____
Destinations _____
15. IP Forwarding
☐ Enable ☐ Disable
16. RIP
☐ Enable ☐ Disable
17. Link Usage Report
☐ Disabled ☐ Peak Usage for All Links

MANET Result

Traffic Sent _____

Traffic Received _____

Delay _____

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