EVALUATION OF AN OPNET MODEL FOR UNMANNED AERIAL VEHICLE NETWORKS

THESIS

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Abstract

The concept of Unmanned Aerial Vehicles (UAVs) was first used as early as the American Civil War, when the North and the South unsuccessfully attempted to launch balloons with explosive devices. Since the American Civil War, the UAV concept has been used in all subsequent military operations. Over the last few years, there has been an explosion in the use of UAVs in military operations, as well as civilian and commercial applications. UAV Mobile Ad Hoc Networks (MANETs) are fast becoming essential to conducting Network-Centric Warfare (NCW). As of October 2006, coalition UAVs, exclusive of hand-launched systems, had flown almost 400,000 flight hours in support of Operations Enduring Freedom and Iraqi Freedom [1].

This study develops a verified network model that emulates UAV network behavior during flight, using a leading simulation tool. A flexible modeling and simulation environment is developed to test proposed technologies against realistic mission scenarios. The simulation model evaluation is performed and findings documented. These simulations are designed to understand the characteristics and essential performance parameters of the delivered model. A statistical analysis is performed to explain results obtained, and identify potential performance irregularities. A systemic approach is taken during the preparation and execution simulation phases to avoid producing misleading results.

Acknowledgements

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Clifton M. Durham

Table of Contents

Page

List of Figures

Figure Page

List of Tables

EVALUATION OF AN OPNET MODEL FOR UNMANNED AERIAL VEHICLE NETWORKS

I Introduction

1.1. Motivation

The Air Force is interested in developing a verified network model that emulates Unmanned Aerial Vehicle (UAV) network behavior during flight, using a leading simulation tool. Through simulation, researchers will be able to predict the expected performance of complex wireless networks. A flexible modeling and simulation environment is needed to test proposed technologies against realistic mission scenarios to: validate architectures and topologies; assess protocols and solutions; benchmark product performance and capabilities; and investigate the impact of changing concept of operations on mission effectiveness [2].

Traditionally, network simulation researchers use simulator to evaluate the higher layers of the Open System Interconnection (OSI) reference model [3, 4]. To develop dependable wireless network simulations, researchers must focus more attention on accurately modeling the wireless physical and medium-access-control layers of the OSI reference model. Specifically, there is a need for a simulation model which incorporates flight mobility characteristics, antenna characteristics, radio propagation, signal interference, and standard communication protocols. Ultimately, there is a great desire for a simulation environment that provides a capability to evaluate several aspects of UAV networks through simulation, in lieu of large test-beds or costly flight testing.

The development of simulation models has provided a strong scientific contribution to the computer networking field, but the accuracy and credibility of published Mobile Ad Hoc Network (MANET) simulation research have come under increasing scrutiny [5, 6, 7, 8]. Thus, this study determines the simulation parameters that reflect the behavior of a UAV network by adhering to strict development and validation procedures; demonstrating that through strict validation techniques, a credible simulation model can be achieved.

1.2. Overview and Goals

The goal of this research is to accurately characterize a UAV communication network physical layer by incorporating key parameters such as antenna radiation patterns, signal interference, transmission power, data rate, and flight mobility effects, as well as validating the simulation environment. The continuous movement of a UAV makes it challenging to accurately model this highly complex communication network in a simulation model. Therefore, observation data collected from an airborne test-bed was used to develop the simulation model in this study. To realistically replicate airborne MANETs in simulations all aspects of the physical layer are modeled. This study also identifies the effects of inherent limitations for a UAV network that may impact mission effectiveness.

1.3. Organization and Layout

In this chapter, the motivations for the research were discussed along with an overview and goals for the research. Chapter 2 presents background material related to

MANET simulation development and execution, and provides insight into recent published MANET research studies. Chapter 3 describes the methodology used for the research experiments. Chapter 4 presents the data and analysis from this research experiment. Chapter 5 gives an overall conclusion of the research performed.

II Literature Review

2.1. Chapter Overview

This chapter presents background material relating to the Mobile Ad Hoc Network (MANET) development and execution in simulation environments. The first part of this literature review presents information on the state of network simulation relating to the MANET community and provides insight into the best practices or approaches to prepare and develop a simulation that produces credible results. The second part of this literature review provides information on the development, execution, and analysis of recent airborne MANET simulations.

2.2. Current State of MANET Simulation Research

Computer simulation is the discipline of designing models of theoretical or real physical systems, using simulation tools for evaluation on digital computers. The proliferation of computers as research tools has resulted in the adoption of computer simulation as one of the most commonly used paradigms for scientific investigation [5]. Much of the knowledge regarding protocol performance for wireless networks results from computer simulations [6]. As a result, the development of simulation models has provided a strong scientific contribution to the computer networking community. However, the accuracy and credibility of published MANET simulation studies have come under great scrutiny.

Early efforts to alert researchers of a crisis in the MANET simulation community took place in May 1999. National Institute of Standards and Technology and US Defense Advanced Research Projects Agency [9] hosted a workshop to discuss challenges and approaches to network simulation. At that time, a recent paradigm shift to using network simulation as a research tool was the reason for aforementioned workshop. Until that time, experimental and mathematical models were the primary methods used in early network research. With networks growing in complexity due to the mix of emerging wired and wireless technology, researchers turned to simulation as a means to understand complex network performance. Heidemann et al. [9] took an early look at how simulation studies were being validated. Their work discussed the importance of network researchers understanding simulation results and ensuring that the validation process provides meaningful answers to the questions being researched.

Pawlikowski et al. [5] conducted one of the first studies on simulation credibility for telecommunication networks. They investigated computer network simulation studies occurring during the period of 1992 to 1998. Their work brought awareness to the fact that "*the majority of the published simulation results lack credibility due to not ensuring two important conditions:*" (1) the use of suitable pseudo-random number generators (PRNG) to ensure simulation independence and (2) the appropriate analysis of simulation output data. The aforementioned conditions were so prevalent that not all network developers and users were enthusiastic about the use of simulation tools, as many spoke of a deep credibility crisis.

According to Pawlikowski et al. [5], a "basic" level of simulation credibility could be achieved if the following reporting guidelines were observed: (1) ensure that the reported simulation experiment is repeatable; (2) specify the analysis method of simulation output; and (3) specify the final statistical errors associated with the results.

Their work highlights the importance of ensuring that the statistical error associated with the final simulation results has the degree of confidence within the accuracy of a given confidence interval. Furthermore, they stress simulation experiments should be controlled and independently repeatable.

In 2003, Perrone et al. [6] examined the state of the MANET simulation community and explored how adjusting certain parameters may affect a simulation's accuracy. Their investigation reiterated the importance of detail required to conduct credible simulation studies. They emphasized the importance of following well-established simulation techniques, of carefully describing simulation scenarios and parameters, and ensuring that the underlining simulation assumptions are understood. Without comprehensive experimental descriptions, it is improbable that anybody would be capable of independently repeating or building upon a simulation study. Their research highlighted the lack of rigor and detail that influences simulation results. They also concluded that the vast majority of MANET simulation studies are performed using a few simulators, namely NS-2, GloMoSim, and OPNET.

The 2005 survey [7] over the 2000-2004 ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc) proceedings exposed significant credibility shortfalls within published simulation studies. From their observations, the authors proposed that simulation credibility is contingent on the following conditions:

1. **Repeatable:** A fellow researcher should be able to repeat the results for their own satisfaction, future reviews, or further development.
2. **Unbiased:** The results must not be specific to the scenario used in the experiment.

3. **Rigorous:** The scenarios and conditions used to test the experiment must truly exercise the aspect of MANETs being studied.

4. **Statistically sound:** The experiment execution and analysis must be based on mathematical principles.

They also informed researchers about the following simulation pitfalls: simulation `setup, simulation type, model validation and verification, PRNG validation and verification, variable definition, scenario development, simulation execution, setting the PRNG seed, scenario initialization, metric collection, output analysis, single-set of data, statistical analysis, confidence intervals, and publishing. MANET simulation-based research is an involved process with plenty of opportunities to compromise the study's credibility.

Andel and Yasinac [8] expressed that simulation generalization and lack of rigor could lead to inaccurate data, which can result in wrong conclusions or inappropriate implementation decisions. They emphasized that if simulations did not reflect reality, they cannot give insight into the system operating characteristics the developers are studying. Table 1 outlines their identified problems and recommendations to improving the credibility of MANET simulation.

Table 1: MANET Simulation Problems and Recommendations

PROBLEM	SOLUTION
Lack of independent repeatability	Investigators provide all settings as external references to research Web pages, which should include freely available code/models and applicable data sets.
Lack of statistical validity	Determine the appropriate number of required independent simulation runs, addressing sources of randomness that may affect independent runs.
Use of inappropriate models	Use two-ray and shadow models which provide a more realistic during data collection and analysis. However, this setting should be validated against some baseline data. This advice relates to the next point.
Improper or nonexistence of simulation validation	Validate the complete simulation against real-world implementation to mitigate the aforementioned problem.
Unrealistic application traffic	Create nodes with real-world characteristics
Improper precision	Use MANET simulations to provide proof of concept and general performance characteristics, not to directly compare multiple protocols against one another.
Lack of sensitivity analysis	Sensitivity analysis can identify a chosen factor's significance. That is, the root cause of measurement deltas, must be fully attributable to an underlying factor. For example, is the difference between two simulated protocols due to the protocols or could it be due to the underlying settings?

2.2.1. Simulations Factors

As stated by numerous researchers, developing a credible simulation requires the appropriate level of detail and rigor. The following paragraphs outline various items to consider when conducting MANET simulations.

2.2.1.1. Simulators

There are a number of simulators available to the MANET community to conduct network research. Table 2 provides insight into the popularity of simulators utilized in 2005.

Table 2: Popularity of Simulations, 2005 [10]

NAME	POPULARITY	LICENSE
NS-2	88.8%	Open Source
GloMoSim	4%	Open Source
OPNET	2.61%	Commercial
QualNet	2.61%	Commercial
OMNet++	1.04%	Free for academic and educational use
NAB	0.48%	Open Source
J-Sim	0.45%	Open Source
SWANS	0.3%	Open Source
GTNets	0.13%	Open Source
Pdns	<0.1%	Open Source
DIANEmu	<0.1%	Free
Jane	<0.1%	Free

Regardless of the chosen simulator, a simulator can only be characterized as dependable and realistic; no network simulator can be described as accurate [10]. Calvin et al. [11] conducted an experience on the accuracy of MANET simulators. Their findings showed that there exists significant divergence between the leading simulators: OPNET, NS-2, and GloMoSim. If a simulator is valid, real-life performance should correlate with the simulated performance [8].

2.2.1.2. Simulation Type and Objective

The 2005 survey by Kurkowski et al. [7] showed that 57.9 percent of the publications they reviewed did not state the simulation type that was being performed. This apparently minor step could lead to a miscalculation in simulation results. The two simulation types that are central to computer network research are: steady-state and terminating simulation. In terminating simulations, the simulation has a specific starting and stopping condition, with a well-defined run-time. Whereas in steady-state simulations, the initial conditions do not matter and it is not important how the simulation terminates. The focus of steady-state simulations is to study a condition in which some specified characteristic of a condition, such as a value, rate, periodicity, or amplitude, exhibits only negligible change over an arbitrarily long period. A steady-state can be accomplished by simulation warm-up. The major reason for the failure of many network simulations is due to the lack of clearly understanding the research goal, and ensuring all objectives are attainable [12].

2.2.1.3. Simulation Size

Simulation users need to understand both what is provided in a simulator and what is appropriate for their experiment [9]. Riley et al. [13] explained that there exists a threshold on the number of nodes in a network for which the results obtained no longer vary as the number of nodes increases.

2.2.1.4. Simulation Warm-up

Research studies by [6, 7] highlighted that researchers tend to pay little attention to the fact that one or more of their sub-models may require initialization or a warm-up time to avoid bias in their simulation's performance. Determining and reaching the steady-state level of activity is part of the initialization, which must be performed prior to data collection. Data generated prior to reaching steady-state is biased by the initial simulation conditions and cannot be used in the analysis [7]. The case study written by Perrone et al. [6] illustrates how the random waypoint mobility (RWM) model could cause considerable errors to a simulation if initialization is not considered. The RWM is based on the following three parameters: pause_time, min_speed, and max_speed. All mobile nodes start out paused and begin to move at the same time: the end of the initial pause. Their work revealed the fact that for the RWM the level of mobility goes through oscillations before settling down onto a *steady state*. The classic solution for this effect is the application of data deletion.

2.2.1.5. Mobility Models

It is critical for network simulation mobility models to match real-world parameters to ensure that simulation results are meaningful [11]. Mobility models are used to define the node movement in MANET simulations. These models fall into two categories: *independent* and *group-based* models. In independent models, the movement of each node is modeled autonomously from other nodes in the simulation. In group mobility models, there is some association among the nodes and their movements throughout the cells or simulation area. Traces and synthetic models are two types of mobility models used in MANET simulation [14]. In the traces models, mobility patterns are observed in real-life systems and imported into the simulation. However, new network environments (e.g., ad hoc networks) are not easily modeled if traces have not yet been created. In this type of situation it is necessary to use synthetic mobility models. These models attempt to realistically represent the behaviors of mobile nodes without pre-observed traces. Previously, researchers relied on randomized mobility models, most commonly on the RWM models [10]. Network researchers are well aware of the negative impact that RWM models have on simulation accuracy. These models are idealistic rather than realistic, because a real-world host will not move randomly without any destination point [15].

2.2.1.6. Radio Wave Propagation Model

Radio propagation is expensive to model (in both development and run-time) and difficult to abstract [9]. Researchers are increasingly aware of the need to develop radio propagation models which include more realistic features, such as hills, obstacles, link asymmetries, and unpredictable fading. Many widely used models embody the following set of assumptions: the world is two dimensional; a radio's transmission area is roughly circular; all radios have equal range; if I can hear you, you can hear me; if I can hear you at all, I can hear you perfectly; and signal strength is a simple function of distance [16].

The two leading network simulators have varying radio propagation models. The NS-2 network simulator has four frequently used models: the Free Space Model, Two-Ray Ground Model, Ricean and Rayleigh Fading Models, and Shadowing models. Whereas, the OPNET network simulator has the following frequently used models: CCIR, Free Space Model, Hata Model, Longley-Rice Model, Terrain Integrated Rough Earth Model, and Wallfish-Ikegami Model. More realistic models take into account antenna height and orientation, terrain and obstacles, surface reflection and absorption, and so forth. Simplistic models can dramatically affect simulation results [16].

2.2.1.7. Routing Protocols

The issues of determining viable routing paths and delivering messages in MANETs are well-documented problems. Factors such as fluctuating wireless link quality, propagation path loss, interference, signal fading, varying topological changes and power consumption affects a MANET routing protocol's ability to provide a reliable communication platform. Generally, two classes of routing protocols have been designed for MANETs, a proactive set of routing protocols (e.g., Optimized Link State Routing protocol) and a reactive set of routing protocols (e.g., Ad-hoc On-demand Distance Vector (AODV) protocol) [17]. Chin et al. [18, 19] looked at the implementation of two distance vector routing protocols using an operational ad-hoc network. During the course of their experiment they discovered a number of problems with both protocols. They [19] highlighted the following four issues for further research:

1. Handling unreliable/unstable links
2. Minimizing the dependency on topology specific parameters
3. Mechanisms for handoff and reducing packet loss during handoff
4. Incorporating neighbor discovery and filtering into neighbor selection sub-layer

Previously, research has demonstrated that routing protocols significantly impact the simulation outcome. For the simulation to be constructive, investigators must clearly understand and document their setting choices within the respective simulation tool [8].

2.2.1.8. Simulation Randomness

Numerous researchers have emphasized the MANET community’s lack of appropriately selecting a PRNG. Kurkowski’s et al. [7] MobiHoc publication survey revealed that none of the 84 simulation papers they reviewed (publications that mentioned PRNG) addressed PRNG issues. Pawlikowski et al. [5] recommended addressing the issues associated with the improper use of PRNG by: ensuring that simulations used a PRNG that is appropriate for the simulation. For example, use a PRNG with adequately long cycles that can be used in more than one simulation; and using an established PRNG that has been tested thoroughly. In the case when using a simulator that has an internal PRNG, such as OPNET and NS-2, researchers should ensure that the seed of PRNG is set correctly for each simulation run.

2.2.1.9. Simulation Validation

Proper validation provides confidence that your simulation tool, environment, and assumptions do not alter the answers to the questions being analyzed. MANET simulation studies pose several challenges to modeling, such as addressing fading, interference, and mobility effects. These factors can produce significant impact to results in the modeled wireless network expected and observed performance. Surprisingly, there are no widely accepted practices that exist to help validate and evaluate trustworthiness of simulation results. Heidemann et al. [9] suggests evaluating simulation sensitivity to help understand how varying configurations change a simulation's accuracy.

2.2.1.10. Simulation Data Analysis

Pawlikowski et al. [5] stressed the importance of conducting the appropriate analysis of the simulation output results. The authors emphasize ensuring that the statistical error associated with the final results has the degree of confidence in the accuracy of a given confidence interval. Non-rigorous output analysis leads to the inaccuracy of many simulation studies. Kurkowski et al. [7] showed that only 12 percent of MobiHoc simulation results appear to be based on sound statistical techniques.

2.3. Related Work

A MANET is a collection of mobile nodes that operate autonomously among themselves over dynamic wireless interfaces. These nodes usually communicate over bandwidth constrained wireless links. Figure 1 shows a fixed wired network connected through a cable or fiber backbone link, while a MANET is dynamically interconnected by a wireless link that does not require an access point. There are several advantages with implementing a MANET, the most obvious advantage is mobility. Mobility provides a great deal of flexibility, which can translate into rapid network deployment, providing an extremely favorable solution to military applications. The Department of Defense's [20] Network-Centric Warfare (NCW) initiative is to develop and leverage information superiority that generates increased combat power by networking sensors, decision-makers, and shooters to achieve shared awareness, increased speed of command, higher tempo of operations, greater lethality, increased survivability, and a degree of self-synchronization.

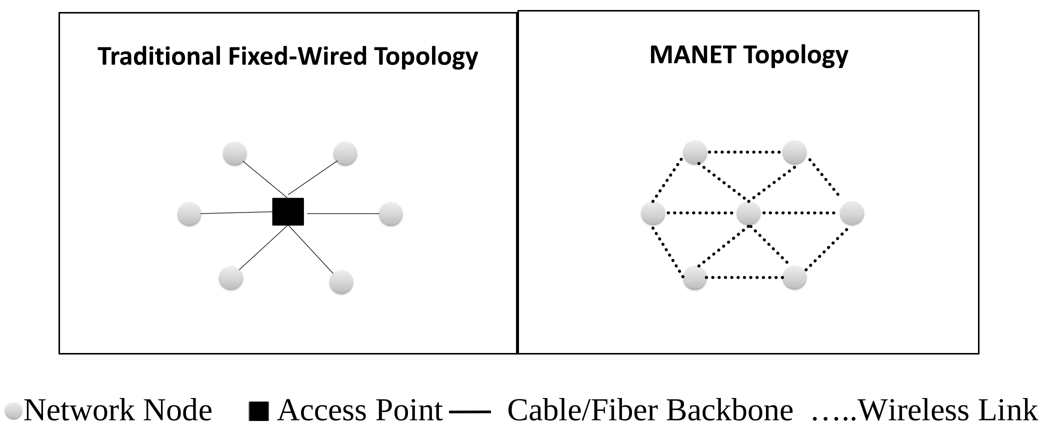


Figure 1: Fixed Wired Network versus MANET

The attraction to MANET technology stems from the ease in which these networks can effectively link several dispersed entities with one another, without requiring a fixed infrastructure. MANET technology provides a means to accommodate a diverse mix of platforms and systems which is critical to the success of military operations [21]. In 2006, the United States utilized UAVs to fly almost 400,000 hours in support of Operation Enduring Freedom and Iraqi Freedom. These UAVs were equipped with wireless transmitters and receivers using antennas to exchange information with other entities.

Despite the fact that MANETs [1] continue to prove their worth in military operations, there are several limitations associated with MANET technology. Many nodes (e.g., micro-UAVs) in a MANET are reliant on batteries or other exhaustible means for their energy, which impact or restrict the time a node is able to function in an area of operation. Another major constraint is limited physical security. Mobile nodes are susceptible to jamming, eavesdropping, spoofing, denial-of-service attacks, and possible physical capture. These threats are often mitigated by applying various encryption and security techniques. But, security comes at a cost to throughput and efficiency. These networks are not usually built with security protocols in mind, but as an afterthought once vulnerabilities have been identified [22]. MANET link reliability continues to be a major concern, since these networks are based on radio waves, the network behavior can be somewhat unpredictable due to propagation problems that may interrupt the radio link. Even with these limitations, MANETs remain a popular choice for military applications.

2.3.1. Traditional MANET Research

Chin et al. [19] reported on their experience of building an operational ad-hoc network that transmitted useful data. The authors' study differs from previous studies in the fact that their work focused on the operational feasibility of existing routing protocols and the effort to create a reliable ad-hoc network. They examined two distance vector MANET routing protocols, Ad Hoc On-Demand Distance Vector (AODV) and

Destination-Sequenced Distance Vector (DSDV). By conducting experiments on a test-bed consisting of two notebooks and three desktop computers, they were able to show that neither protocol could provide a stable route over any multi-hop network connection. Each protocol was fooled by the transient availability of the network links to nodes that were more than one hop away. A fading channel caused the routing protocols to conclude incorrectly that there was a new one hop neighbor. The results from their research test-bed versus the results from a simulation environment differed. The simulation application they utilized provided an inaccurate assessment of actual protocol performance. They suspected that the results dissimilarity was due to the use of a simplistic radio propagation model that was standard in the simulation package. They recommended using realistic radio propagation models that incorporated channel fading and other important wireless channel characteristics. This thesis examines the OPNET radio propagation model to ensure that the model adequately supports our UAV network. This objective is accomplished by comparing our simulation results with actual flight test performance metrics in order to validate the model.

2.3.2. Airborne MANET Studies

Preston et al. [23] used real-world data to look at the quality of service over airborne radio links which experienced periodic outages due to line of sight occlusion caused by the aircraft's wings and tail. Their study extended the standard OPNET models so that the pointing direction of an antenna affixed to a moving aircraft could be determined in three-dimensional space. OPNET Version 10.5 and earlier did not support node mobility modeling with six degrees of freedom. Earlier versions only provided mobile node position in three degrees of freedom: latitude, longitude, and altitude. OPNET Version 11.0 and later includes three additional degrees of freedom: roll, pitch, and yaw. However, initially the standard OPNET pipeline stages did not take advantage of these new degrees of freedom. Due to this fact, Preston et al. modified a user supplied "Enhanced Antenna Positioning" model to include all six degrees of freedom. In addition, they also modified the OPNET receive and transmit antenna gain pipeline stages to incorporate all six degrees of freedom in order to describe the motion of an antenna mounted to an aircraft in flight. The radio transceiver pipeline stages in Figure 2 consists of 14 stages that exhibit the radio link behavior performing all the wireless physical layer operations. Each pipeline stage can be modified or substituted to fit the experimental goals.

According to Law and Kelton [24], the most definitive test of a simulation model's validity is establishing that its output data closely correlate to the output data that would be expected from the actual system. To validate these enhanced OPNET models, Preston et al. [23] designed a scenario based on communication between the United States Air Force's Paul Revere test aircraft and a ground station. Their research clearly showed that as the aircraft changed altitude and position, so should the antenna pointing direction, to obtain accurate simulation results.

Their experiment showed a good correlation between the OPNET model they developed and the Paul Revere flight test data, but there were instances in the simulation that did not match the flight data. These anomalies were the result of an imprecise antenna, and the fact that the antenna pattern in the simulation study did not match the Paul Revere aircraft antenna.

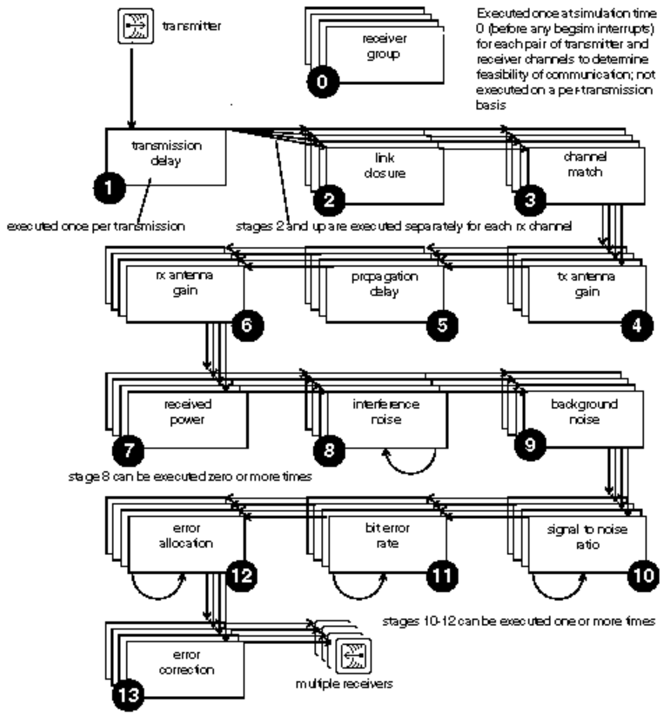


Figure 2: OPNET Transceiver Pipeline Stages [25]

This thesis intends to follow a similar approach, but we conduct multiple simulations comparing communication performance based on three sets of test data. This approach supports our claim that airborne MANET simulations must incorporate real trace models, as well as incorporating the suitable level of detail in model development.

Denson et al. [26] modeled the performance of MANETs with random and predetermined mobility patterns using OPNET. They analyzed how well sensor nodes were able to form a cluster, and maintain a formation with varying update intervals between the nodes and the mobile base station. Their research relates closely to NCW scenarios, where sensor nodes are deployed randomly from an aircraft onto the area of operation with the expectation that a cluster would be formed to collect information on the environment or on adversary troop movement. The authors implemented a scenario consisting of four mobile nodes and a signal mobile base station to show the effect of reference point broadcast interval on the position error of the mobile nodes and the mobile base station power consumption per packet transmission. But, they had to specify three additional attributes in the standard OPNET *manet_station_adv* model to characterize the behavior of their scenario. These attributes are defined as:

- **Movement Pattern:** defines a node to be either a base station, or a simple mobile node
- **Follow Target:** defines which group the node belongs to, in the case where a node is not a base station
- **Follow Distance:** defines the distance in meters which the mobile nodes should maintain from the central base station.

Their research demonstrates the flexibility of the OPNET simulation package to model complex scenarios that would otherwise be costly to execute in real-world test environments. Our research provides another example of how OPNET models must be modified or substituted to emulate a real-world system. Proving it is essential to examine standard OPNET models to ensure that these models meet the experiment requirements.

To support their Unmanned System Initiative, the US Army partnered with Auburn University to develop a high fidelity modeling and simulation test-bed for Army UAVs [27]. The control station that the soldiers used to communicate with a UAV was required to connect to a base station antenna on the ground utilizing over 400 feet of various cables. This setup presented a major problem in that it was time consuming to set the system up and take down. The large radio footprint presented a potential risk of the enemy determining the base station location through RF triangulation. The Army addressed this problem by developing a simulation test-bed to evaluate secure wireless alternatives to replace the troublesome setup. The Army had the need to do verification and validation (V&V) to ensure that the test-bed had appropriate predictive power. Through proper V&V, the simulation or test-bed can be used to test various network configurations. They used parts of actual field data as a means to build their test-bed, and the remaining data to determine whether the model behaves as the system does. The author points out that one must be concerned that conceptual models correctly abstract the unimportant details while still capturing the attributes that drive the simulation. This thesis utilizes the simplified version of modeling process outlined in Figure 3 which depicts the simulation V&V process.

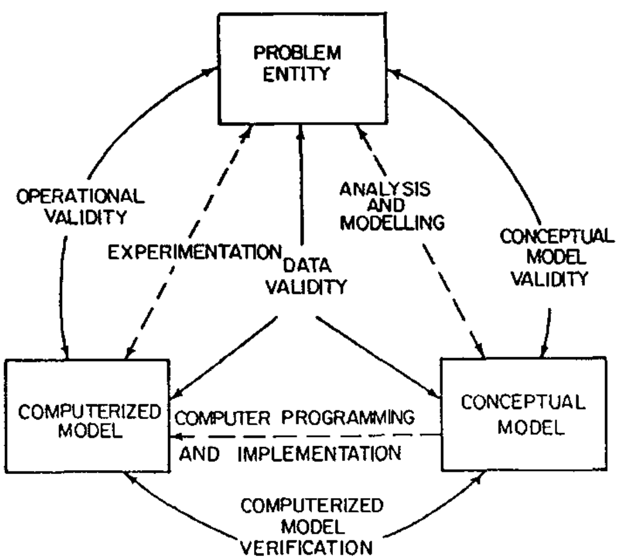


Figure 3: Simplified version of the modeling process [28]

They [27] also calibrated their model by using input scripting. They took actual field test data and configured the simulator to read the inputs. They then used the simulation test-bed to evaluate potential designs to solve their problem. Their study successfully followed four commonly accepted scientific method steps outlined by [29]:

1. Ability to observation of the system
2. Ability to account for observed behavior
3. Ability to predict future behavior based on assumption that the modeling understanding is correct
4. Ability to compare the predicted behavior with actual behavior

In addition, they made modifications to the 802.11g wireless model in OPNET to simulate the transmission of UAV data over a wireless network. The result of their research was UAV simulations that furthered the goal of making UAV command stations more mobile. The author has plans to extend this model in both Qualnet and NS-2.

The military is constantly searching for ways to enhance Network-Centric Warfare. Airborne networks consisting of command and control aircrafts such as the Airborne Warning and Control System, Rivet Joint, Joint Surveillance Target Attack Radar System, and UAVs are critical to NCW objectives. An airborne network often consists of high-bandwidth links that periodically suffer outages at predicable times due to aircraft banking (e.g., roll, pitch, and yaw) in flight profiles [30]. Butler et al. investigated a methodology for emulating MANETs during a flight test utilizing an airborne network based on wide-body aircraft. Figure 4 shows the testing architecture used in their experiment which is comprised of a single aircraft, two simulated airborne nodes, and two emulated MANETs.

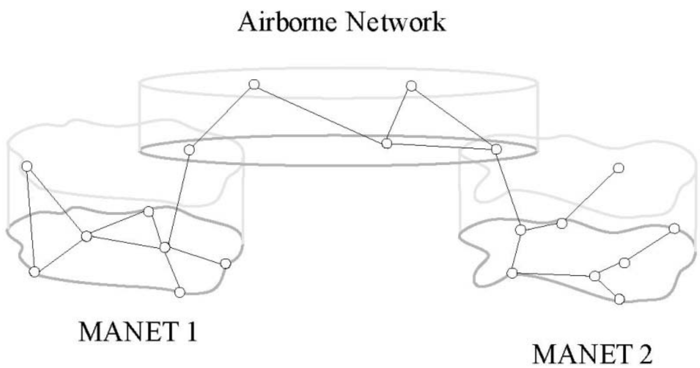


Figure 4: Interconnected MANETS [30]

Bulter et al. [30] designed each MANET node to consist, at a minimum, of a radio and a router. In addition, some nodes included a host, or hosts, and a gateway. In the case when nodes were not in direct radio contact with each other or with MANET nodes serving as gateway, a router function was included to allow nodes to communicate beyond a single hop. They were able to emulate the MANET networks by making a series of simplifying design choices and assumptions. These assumptions and design choices can be found in [30]. The scenario consisted of two MANETs in separate locations with nodes traversing the network. When a node entered, a MANET a route was created and added to the routing table. In addition, they created an application to collect and record all of the data entering and leaving the MANET during the flight test. Their research identified several fundamental issues and problems involved with supporting the MANETs over the Airborne Network. Specifically, they noted that the aircraft flight profile during banks to turn blocked the transmission signal. Regardless of whether the antennas were Omni-directional or directional, mounted in the nose, belly, or on the roof of the aircraft, some blocking by the aircraft body was likely to occur. It is possible to minimize the loss of connectivity by switching between multiple antennas on board the aircraft to create a new connection as the aircraft proceeds through the flight profile [30]. In addition, Swanson [31] conducted a recent experiment involving airborne networks. His study was able to show that the OPNET model developed for the Tactical Targeting Network Technology (TTNT) Airborne Network accurately represented the real-world concept. The systematic approach used to conduct the research was essential to accurately validate and verify the TTNT OPNET model.

2.4. Wireless Networking

Wireless networking involves getting information from one location to another location using electromagnetic waves, such as radio waves. Wireless telecommunication has a significant impact on the way the United States military conducts combat operations. There is no aspect of military operations that wireless communication does not support, ranging from using cellular phones to a fully functional airborne MANET; wireless communication enhances the combat operator’s to ability share information. Emerging wireless communication technologies have lead to wired networks being replaced by more flexible wireless networks at an exponential rate. These technologies address the military need to have information accessible to all elements of the force at any time and any place through the use of manned and unmanned vehicles. Figure 5 illustrates the Global Information Grid (GIG) concept adopted by the Department of Defense in 2002. Wireless networking continues to be an essential component to successfully implementing the GIG objective of providing authorized users with a seamless, secure, and interconnected information environment, meeting real-time and near real-time needs of the warfighter [32].

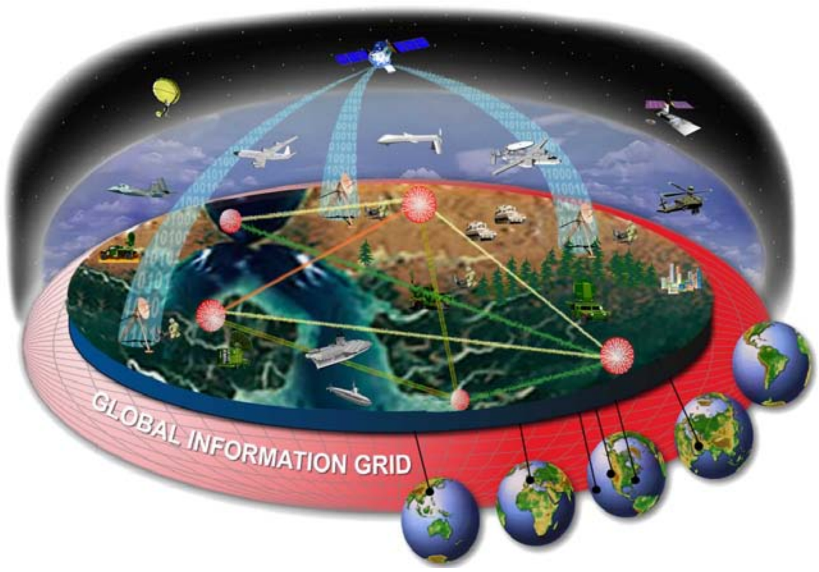


Figure 5: Global Information Grid [32]

In order for wireless communication to provide military forces with a seamless information environment, several technical challenges must be addressed, such as network unpredictability, bandwidth and power limitations, security, latency, availability, and link quality. Modeling and simulation research is instrumental in solving many of the above issues.

2.4.1. Physical Layer Protocol

The OSI Physical layer is responsible for the transmission of raw bits over the physical link connecting network nodes. A transmission link can consist of either a wired or wireless medium. This layer includes specifications for electrical and mechanical characteristics such as: signal timing, voltage levels, data rate, maximum transmission length, and physical connectors of networking equipment. Figure 6 shows the seven layer OSI model which depicts how network protocols and equipment interact and communicate with each other [33, 34].

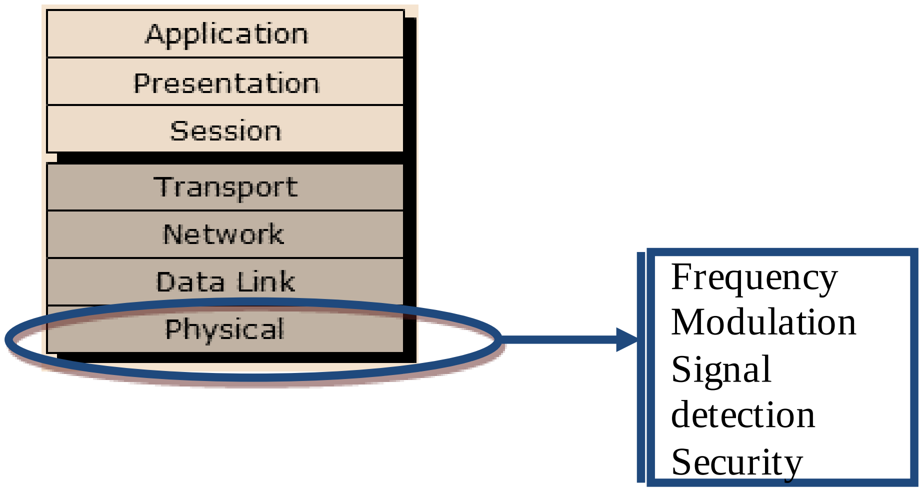


Figure 6: Seven Layer OSI Model

The physical layer of the OSI model is the first layer of the model. Its purpose is to define the relationship between a device (adapters, router, hubs, etc.) and a physical medium (guided or unguided). In wireless networks, nodes usually use radio frequency channels as their physical medium. Since the nodes in a wireless network are not physically connected, there is a great deal of flexibility with implementing a wireless network.

As stated by a previous MANET study [35], characterizing the physical layer brings many challenges due to the complexity and unpredictability associated with wireless communication links. Wired network models have advanced to a degree that researchers understand the physical layer parameters that significantly affect the accuracy of simulation results. As a result, suitable wired abstractions have been developed. While in wireless networks there is less information regarding the appropriate level of detail required to ensure the correctness of network simulations.

Heidemann et al. [3] describe the trade-offs associated with adding detail to simulation models. They looked at the effects of detail in five case studies of wireless simulations for protocol design. They pointed out that too little detail can produce simulations that are misleading or incorrect, while adding detail requires time to implement, debug, and later change. A side-effect of adding detail is that it slows down the simulation, and can distract from answering the intended research question. They stated that a “fully realistic” simulation is not possible, and the challenge to simulation designers is to identify what level of detail is required to answer the design questions at hand. Consequently, choosing the right level of detail for a wireless network simulation is not a trivial task.

Takai et al. [4] point out that researchers traditionally develop simulation models that are used to evaluate devices and protocols, such simulations usually focus on higher layers OSI reference model (e.g., network, transport). They present several factors at the physical layer that are relevant to the performance evaluations of higher layer protocols. These factors include signal reception, path loss, fading, interference and noise computation, and preamble length. Modeling the physical layer for our research requires sensitivity analysis of the aforementioned factors to accurately reproduce the system under evaluation.

2.4.2. Antenna Characterization

Antennas have become an indispensable component of military communication infrastructure. The antenna selection is one of the most important components in any radio communication system. As a result, properly defining the antenna radiation pattern of a mobile node is essential to replicating the network in a simulation. Two very important parameters related to the design of antennas are *gain* and *directivity*.

Antenna gain is the measure in decibels how much more power an antenna radiates in a certain direction with respect to a hypothetical ideal isotropic antenna, which radiates equally in all directions. Thus, gain is calculated by using:

$$G = \frac{P_{max}(AUT)}{P_{max}(\text{isotropic antenna})} \times G(\text{isotropic antenna}) \quad (1)$$

where P_{max} (AUT) is the maximum power density of the Antenna Under Test (AUT), P_{max} (isotropic antenna) is the maximum power density of the ideal reference, and G(isotropic antenna) is the known gain of the ideal reference antenna. Directivity is equal to the ratio of the maximum power density $P(\theta,\varphi)_{max}$ (watts/m^2) to its average value over a sphere as observed in the far field of an antenna. Thus, directivity from pattern is calculated by using:

$$D = \frac{P(\theta,\phi)_{max}}{P(\theta,\phi)_{avg}} \quad (2)$$

Non-isotropic antennas are characterized by how much more intensely the antenna radiates in its preferred direction than an ideal reference antenna would when transmitting at the same total power [36]. Figure 7 demonstrates two types of antenna patterns. The Antenna on the left represents an isotropic Omni-directional antenna, in which the beam radiates equally 360°. In contrast, the antenna pattern on right represents a highly focused beam that intensifies power in a particular direction. The narrower the beam is, the higher the gain is (and the range), because you eliminate more unwanted emissions and background noise in the other directions.

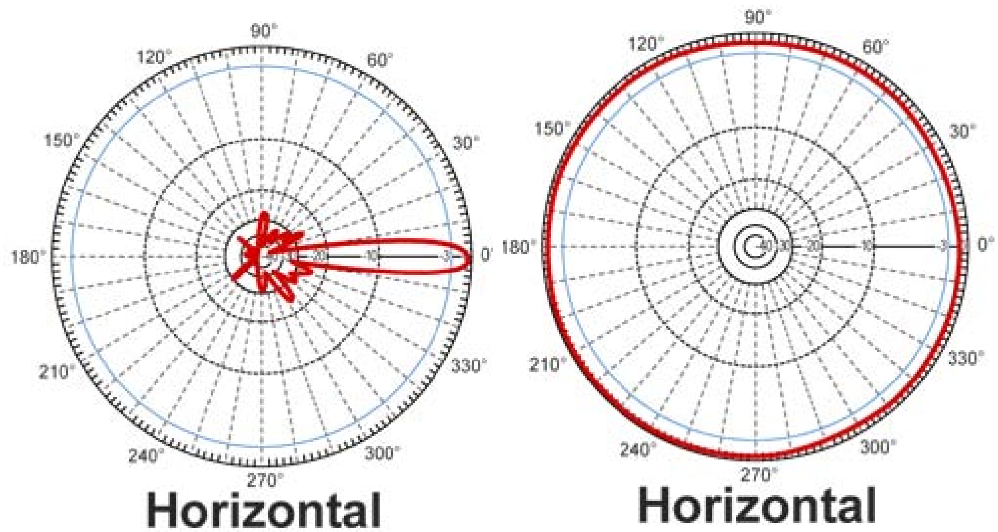


Figure 7: Directional versus Omni-directional

2.4.3. Range Factors

The receiver ultimately determines the performance of the wireless link. The link range depends on the sensitivity of the receiver. A receiver's sensitivity is a measure of its ability to discern low-level signals and still correctly translate it into data. A signal cannot be processed if the noise magnitude added by the receiver is larger than that of the received signal. The lower the sensitivity level of the receiver the better the hardware. For example, a receiver with a sensitivity of -100 dBm is better than a receiver sensitivity of -93 dBm, thus able to hear a weaker system. Also, receivers require a minimum

Signal-to-Noise (SNR) ratio to successfully decode the received signal. SNR defines the difference of power in the receiver between a meaningful signal and background noise. Note dBm is an abbreviation for the power ratio in decibels (dB) of the measured power referenced to one milliwatt.

It is a well-known fact that power is a precious resource in MANETs. Nodes are usually powered by batteries that are constrained by weight and size. High transmit power emission will likely drain the battery faster or cause interference between nodes in close proximity. In fact, energy constraints affect almost all wireless network protocols in some manner, so energy consumption must be optimized over all aspects of the network design [37].

Additionally, the radio transmission range is affected by the environment in such a complex way, which makes it very difficult to predict the behavior of the network. Transmission paths and parameters change instantaneously due to obstructions and environmental changes. Particularly, radio signal propagation is subject to diffraction, reflection, and scattering. In the case of diffraction, the signal bends around an object causing sharp irregularities by obstructing the path between transmitter and receiver. Reflection occurs when signal waves strikes the earth surface, buildings, and walls get reflected. Finally, scattering is caused by very small obstacles such as rough surface, foliage, lampposts, street signs, etc. Hogie et al. [10] stated no simulator implements all three properties of radio propagation.

Attenuation is another important factor that impacts the range of a radio transmission. It is the decrease of signal strength between the transmitter and the receiver.

In the air, the attenuation is simply proportional to the square of the distance. So, when the distance doubles, the signal becomes one-fourth less strong. In addition to distance, environment conditions make the attenuation change over time.

2.5. Chapter Summary

This chapter discussed the background material relating to the development and execution of Mobile Ad Hoc Network (MANET) simulations. The first part of this literature review presented information on the state of simulation relating to the MANET community, and provides insight into the best practices or approaches to prepare and develop a simulation that produces credible results. The second part of this literature review provided information on the development, execution, and analysis of recent airborne MANET simulations.

III Methodology

3.1. Introduction

Chapter 3 defines the methodology used to conduct a performance evaluation of a UAV simulation model that emulates an ad hoc network during actual test flights. The systematic approach of the performance evaluation used in this paper allows the experiment to be independently repeated, if desired.

The main research objective is to develop a verified simulation network model that emulates UAV behavior during flight by applying wireless simulation best practices and lessons learned identified by the Mobile Ad Hoc Network (MANET) simulation community. Properly validating a simulation against the real-world implementation and environment can mitigate many of the problems associated with simulation modeling, such as incorrect parameter settings and improper level of detail [8].

3.2. Problem Definition

3.2.1. Goals and Hypothesis

There are no well-accepted procedures to validate wireless propagation models and user mobility models in MANET simulations. The goal of this research is to accurately characterize the behavior of an UAV communication network by incorporating the effects of antenna radiation pattern, signal interference, and flight mobility, as well as developing a validated simulation model. The continuous movement of a UAV makes it challenging to accurately duplicate this highly complex and dynamic communication network in a simulation model; we must take into account six degrees of freedom:

latitude, longitude, altitude, roll, pitch, and yaw. To realistically replicate a network in simulation all six degrees of freedom of an airborne mobile node are modeled. This study also identifies the effects of inherent limitations of a UAV network that may impact mission effectiveness.

Historically, MANET researchers largely focused on analyzing the effect of only three degrees of movement for a mobility node (latitude, longitude, and altitude). This research extends the analysis to investigate the impact of three additional factors: roll, pitch, and yaw. By accurately incorporating the above factors in this research, the underlining physical settings that have a significant impact of the accurately of UAV simulation model are recognized, and a realistic representation of the network is captured.

This study determines the simulation parameters that reflect the behavior of a UAV network's physical layer by adhering to strict validation procedures. Thus, demonstrating that using strict validation techniques a credible simulation model can be achieved.

3.2.2. Approach

The performance metrics collected from the network characterization herein are compared to existing UAV flight test data. These comparisons provide insight into the factors and parameters that affects the validity of a UAV simulation. The primary objective is to develop a realistic and credible simulation model. By evaluating the sensitivity of simulation parameters in OPNET, understanding how varying configurations change the behavior and performance of an operational UAV network in various scenarios will be gained. Therefore, extensive validation is accomplished and parameters critical to the accuracy of this simulation characterization are added as needed. Thus, an iterative approach is used to produce the final model and appropriate settings. Data collected from actual flight tests is used to design the simulation, and determine whether the model behaves as a UAV network does.

The results answer the question: how do the effects of node mobility, antenna occlusion, and interference impact an airborne network? This approach determines whether the aforementioned simulation attributes accurately represent real-world implementation of the UAV network modeled in this research.

3.3. System Boundaries

Figure 8 shows the system under test for this research is a UAV network that includes a mobile aerial node and a communication link with a stationary ground station receiver. This study focuses on evaluating the steady-state behavior of the UAV network physical layer. The UAV sends data to the ground station using a wireless radio adaptor. Performance is measured by various characteristics of the data packets successfully received by the ground station. The impact of node mobility and the antenna radiation pattern on link quality during several points throughout a flight is determined.

The component under test (CUT) is the physical layer of the network. To limit the scope of this research, the upper OSI layers (Layers 2-7) are modeled as a simple constant rate source sending a packet stream. Figures 9 and 10 shows the transmitter and receiver physical layer node models implemented in OPNET.

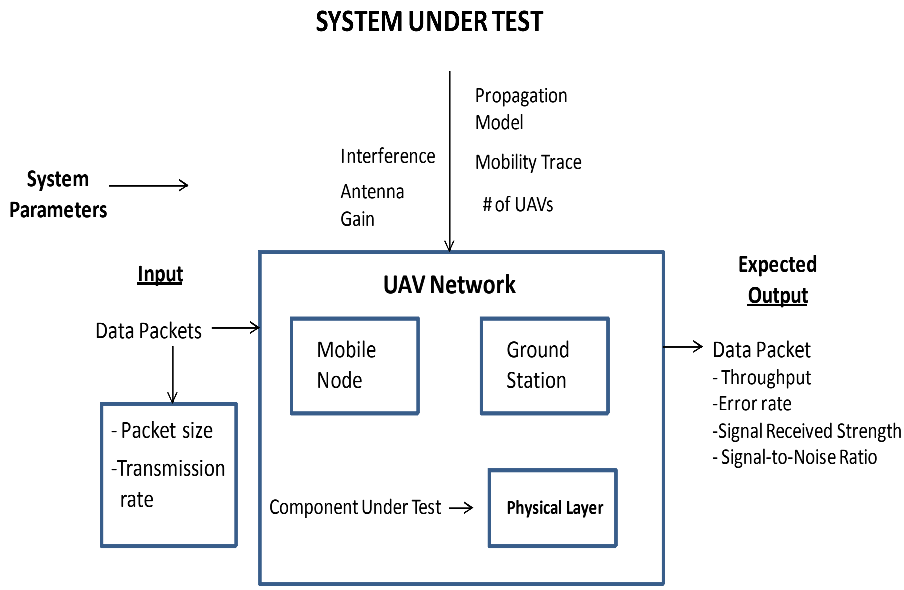


Figure 8: The UAV Network

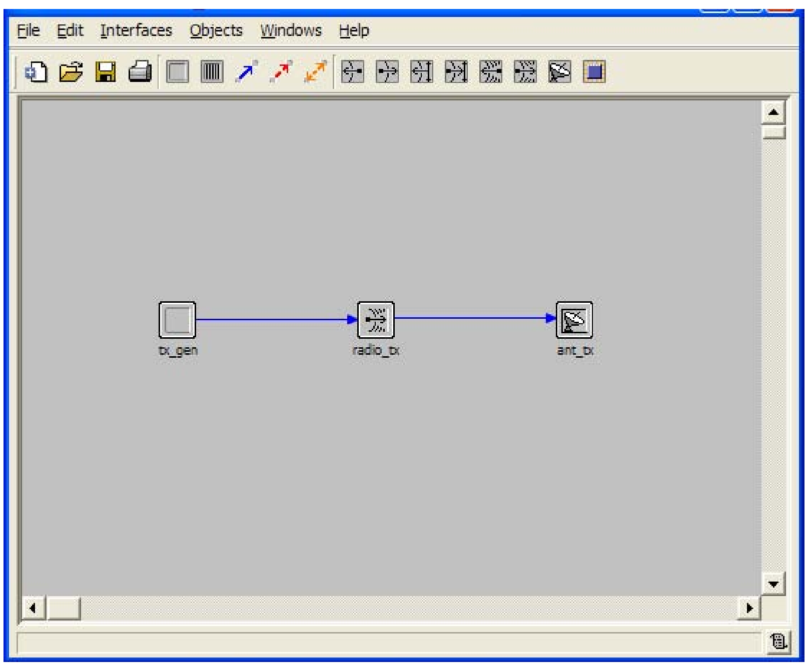


Figure 9: Transmitter Node Model

Isolating the evaluation to the physical layer allows a comprehensive analysis of the fundamental characteristics that make ad hoc mobile networks significantly different from traditional wired networks.

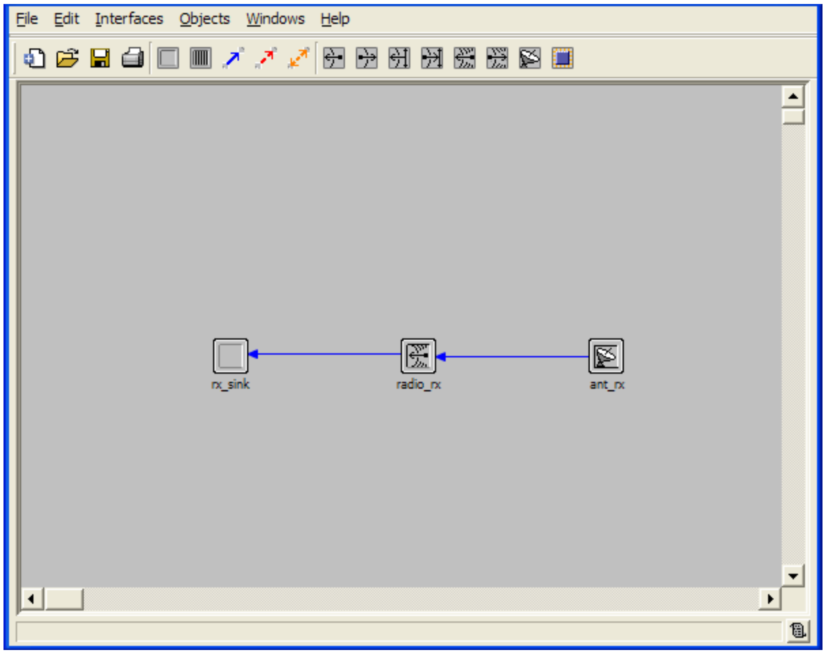


Figure 10: Receiver Node Model

3.4. System Services

The system offers one service, data transmission from a single UAV to a stationary ground station. The UAV network transmits data to a ground station receiver. There are three possible outcomes: successful delivery, delivery with bad blocks, or delivery failure. Success occurs when the ground station successfully receives all the transmitted packets. Delivery with bad blocks occurs when the ground stations receives blocks with errors. The final outcome, delivery failure, occurs when the ground station does not receive packet transmission from the UAV platform. All three outcomes will occur in a realistic MANET. These results determine what physical layer parameters settings best suit an airborne UAV network.

3.5. System Workload

The workload for this system is the data packet transmitted from the UAV platform over the communication link to the ground station. The packet payload is flight data consisting of: local time, data, GPS fix quality, latitude, longitude, elevation, speed, heading, signal strength, roll, pitch, and yaw. This workload is essential to this study because it is the only measurable input into the system. For purpose of this study, the packet size and transmission rate remains constant to limit the scope in order to focus specifically on the physical layer, and to match the flight test data collected from previous UAV flight tests. The performance of multi-hop routing protocols is not of current interest, but may be feasible for future work once a validated UAV simulation is available. The simulation reads actual flight position data to build its flight path used in place of unrealistic mobility models, such as the RWM.

3.6. Performance Metrics

According to Heidemann [9], to properly validate a simulation model one must accurately define performance metrics to compare simulation model results. Adequately defining metrics ensures that simulation model performance reflects the behavior of a realistic environment or operation. The following performance metrics are of interest in this research:

Throughput - is the rate at which packets are sent through the channel in seconds. It is represented as the average number of packets, or bits, successfully received by the receiver per second. Throughput is calculated by OPNET using

$$\text{Throughput} = \text{Packet\_Average}/\text{Sim\_Time} \quad (3)$$

where *Packets_Average* is the number of packets accepted to date, while *Sim_Time* is the current cumulative simulation time.

Received Power - is a key factor in determining if the receiver correctly captured the packet information. Received power is only calculated for packets that are classified as valid. This metric represents the average power of a packet arriving at a receiver channel. The received power is updated at the start of each packet, and drops to zero when the packet ends.

Signal-to-Noise Ratio (SNR) - is an indication of potential background interferences with the wireless signal. It is typically calculated as the ratio of a signal power to in-band noise power, measured at the receiver location. The higher the ratio, the less interference the background noise causes. A research goal is to measure the propagation delay experienced by the network as a function of the SNR (dB) to show the expected trend in delay performance at the physical layer. SNR is calculated in OPNET by using

$$\text{SNR} = 10.0 * \log10\ (\text{rcvd\_power} / (\text{accum\_noise} + \text{bkg\_noise}))) \quad (4)$$

where *rcvd_power* is the average received power; *accum_noise* is the accumulated average power of all interference noise; and *bkg_noise* is the average power of all the background noise.

Received Signal Strength - is a function of distance from the transmitter and the signal power (dB) to the receiving antenna. Signal strength decreases with distance and is related to SNR.

Error Rate - is defined as the number of erroneous bits received divided by the total number of bits received. In a wireless environment there are many factors, such as interference, distance, and signal-to-noise ratio, which contribute to a high bit error rate.

Dropped Packets - is the number of transmitted packets that are not received by the destination node. This metric is the total number of packets transmitted subtracted by the total number of packets successfully received by the destination node.

3.7. Workload Parameters

Table 3 lists the workload parameters for this research. The primary workload is packet transmission from a UAV transmitter to a ground-station receiver. A normal distribution with a mean of 250 bytes (2000 bits) is used to provide the packet size within OPNET. Packets are generated using the "simple source" process model. The packet interarrival time is approximately 0.2 seconds. These parameters were chosen based on data available from the real-world flights.

Table 3: Workload Parameters

PARAMETERS	DESCRIPTION
Packet Size	Packet size for this experiment varies to emulate realistic data transmitted by the real-world test-bed. The payload consists of such parameters as: latitude, longitude, direction, elevations, speed reading, and received signal strength indication. These parameters support the development objective to use empirical data in the simulation model design process.
Transmission Rate	This is the rate that data is transmitted over the communication link. Data is transmitted at a constant rate based the trace model scenario. This parameter is instrumental to correctly calculate the network throughput.

3.8. System Parameters

The system parameters are those characteristics of the system that are of interest to accomplishing the research objectives. Other system parameters, such as transmit power, protocol, and signal type will be configured based on flight test data. Table 4 explains the system parameters used in this research.

Table 4: System Parameters

SYSTEM PARAMETER	DESCRIPTION
Antenna Gain	It is well-known that antenna types (e.g., Omni or directional), as well as their orientations can greatly affect the performance of wireless links [38, 39]. A realistic antenna pattern is necessary to characterize the UAV network behavior.
Interference Noise	Interference is a fundamental aspect of wireless networks. Understanding interference effects is essential to modeling the wireless network performance.
Mobility Trace	The trace model is duplicated from real-world flight data. For this experiment the node altitude will not exceed 200 meters. Its range is calculated as the distance of the UAV platform from the ground station. The UAV range does not exceed line of sight. The UAV's speed varies based on the scenarios type being modeled. Speeds for this experiment do not exceed 50 knots. Historically, MANET research studies made unrealistic assumptions regarding node mobility [10]. A realistic mobility model is necessary to accurately characterize the network behavior. If possible use trace models or realistic data to represent the mobile node behavior.
Propagation Model	RF Propagation is another importance aspect to conducing creditable MANET simulation research. Radio Propagation is more difficult to model than wired channels. This research model considers diffraction, refraction, and scattering effects on transmission quality.
# of UAVs	# of UAVs is the number of mobile nodes transmitting packets to the fixed ground station.

3.9. Factors

The factors are a subset of the parameters that are varied during experimentation. Table 5 outlines the factors for this research. These factors support the primary focus of our research, which is to analyze the impact of node mobility and antenna characterization on wireless network. Our experiment is organized into one main scenario that consists of three separate antenna configurations that is evaluated against three trace models.

Table 5: System Factors

SYSTEM PARAMETER	**DESCRIPTION**
Antenna Radiation Pattern	Antenna radiation pattern is a 3-D plot of the relative field strength transmitted from or received by the antenna.
Trace Model	Adjust the simulation mobility model settings: roll, pitch, and yaw. This experiment uses three different flight scenarios based on actual flight data to evaluate and validate system behavior.

3.10. Evaluation Technique

This study compares simulation results with actual UAV network performance results. It verifies that the simulation model is realistic, by ensuring it exhibits the operational UAV flight behavior. In Chapter 4 we provide a comparison of aggregate statistical measurements from actual flights tests and the simulation runs to provide a useful picture to make our assessment.

OPNET modeler 14.0 [25] characterizes the system under test behavior. OPNET is a simulation tool that includes hundreds of pre-built models to study the performance of communication networks. The tool has an extensive wireless capability, which provides the ability to model all wireless transmission aspects, including radio frequency propagation, interference, transmitter/receiver characteristics, and node mobility.

OPNET allows the system under test to be evaluated by simulation in lieu of more costly alternatives, such as using a large scale test-bed or an operational system to conduct the experiment. OPNET offers many standard communication components that are useful and provide significant efficiencies when constructing complex communication models. However, it is important for users to be familiar with sub-model limitations in the OPNET standard library, such as using model components developed or validated for a given scenario.

3.11. Experimental Design

The scenario used in this study consists of a single UAV transmitting data packages to a single ground station, both the transmitter and receiver are equipped with a Microhard 320 Ultra High Frequency hopping wireless modem. Table 6 lists the modem specifications important to this study.

Table 6: Microhard Specifications

PARAMETERS	VALUE
Frequency	310-390 MHz
Channel Bandwidth	Depends on link rate
Selectable Channels	16,000 at 6.25kHz
Range	60+ miles (dependent on link rate and line of sight)
Sensitivity	-107dBm @ 115.2kbps link rate -115dBm @ 19.2kbps link rate
Output Power	100mW – 1W

The simulated UAV flies in a flight based on three trace models recorded from real-world test flights. The UAV GPS positional data and the static ground node coordinates allow the analysis of various performance parameters as functions of distance. The UAV generates a normally distributed stream of 250-byte packets. The purpose for having a single node UAV as the sole transmitter is to avoid possible packet collision due to simultaneous transmissions. The ground node captures the broadcast packets and records it transmit timestamp, sequence number, size, and receive signal strength indication (RSSI). A typical scenario lasts from 12-15 minutes. The UAV is controlled by autopilot with a predetermined flight path. The simulated UAV node moves according to a predetermined flight path. A trajectory file is loaded into OPNET to permit the node to move according to the latitude, longitude, and altitude of real-world test flights. Table 7 lists the experiment parameters used in the simulation model that allow the transmitter and receiver to establish a transmission link; according to the real-world system parameters.

Table 7: Fixed System Parameters

PARAMETERS	FIXED VALUE
Size of region	1500m x 1500m
Path loss model	default
Data rate (bps)	64,000
Packet formats	Unformatted
Bandwidth (KHz)	172
Minimum frequency (MHz)	370
Modulation	Binary phase-shift keying
Receiver processing gain (dB)	-40 dB
Transmitter power (W)	1.0
Noise figure	1.0
Transmission rate	1 packet/.2 sec

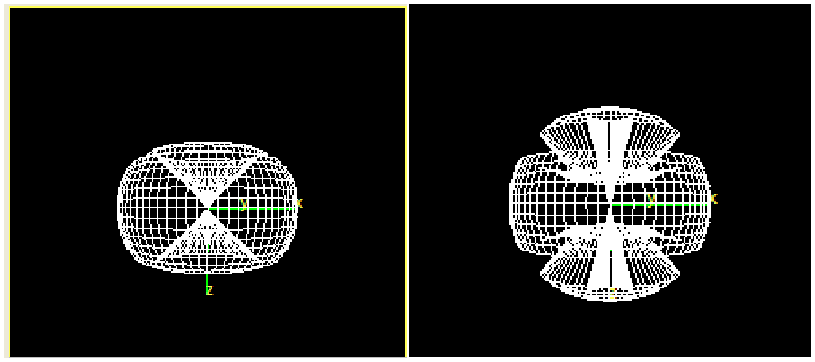
Designing a realistic antenna model is also essential to creating a credible simulation model that behaves as the real system. Vlah [40] conducted a study on antenna selection performance in 802.11 networks that explored the use of antenna selection as a new avenue of performance improvement in mobile wireless ad hoc networks. They were able to show that antenna selection led to improved performance. Table 8 lists the important antenna attributes used in our study.

Table 8: Antenna Attributes

NAME	VALUE
Antenna model	Omni-directional
Receiver Antenna Gain	-.3dBm
Transmitter Antenna Gain	+3 dBm
Ground Antenna pointing ref. theta	180 degrees
Ground Station altitude	396 meters
Ground Station latitude	41.885
Target longitude	-71.944
Transmission power	1 Watt

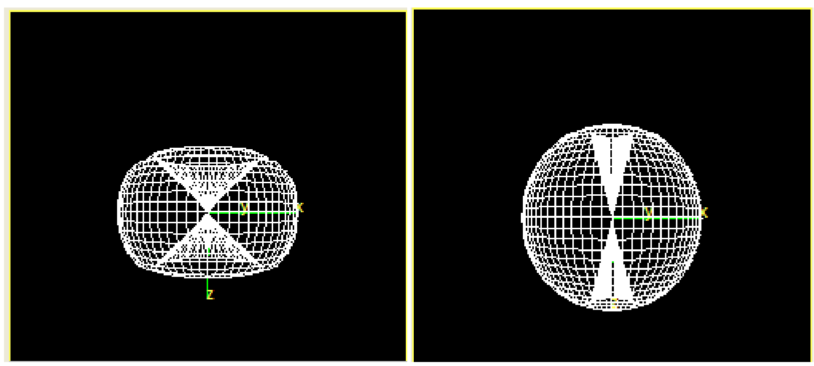
OPNET Antenna Editor was used to create the antenna models used in this research, based off of the actual test-bed antennas. The ground station consists of an Omni-directional antenna with an average gain of -.3dB. The ground station site has a -40 dB attenuation due to cable loss. The UAV consists of an Omni-directional antenna with an average gain of +3dB.

We utilize three antenna configurations under test in this study. Antenna Setup #1 consists of a detailed antenna pattern for both the UAV and ground station. While, Setup #2 consists of a detailed antenna pattern for the UAV node and less detail for the ground station. Finally, Setup #3 consists of a generic isotropic antenna model at each node, allowing for a 360 degree spherical footprint. Figures 11, 12, and 13 display the custom antenna radiation patterns used in this study.



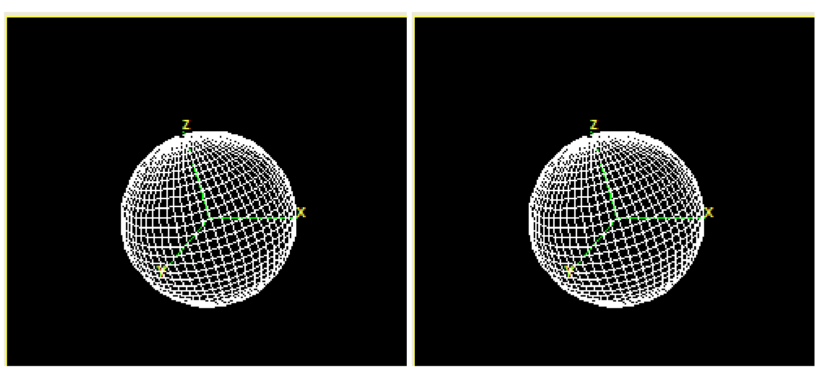
UAV Ground Station

Figure 11: Antenna Configuration #1



UAV Ground Station

Figure 12: Antenna Configuration #2



UAV Ground Station

Figure 13: Antenna Configuration #3

A full-factorial design in three levels with two factors is used for this experiment. It is a common experiment design in which every setting of every factor appears with every setting of every other factor. Also, experiment replication provides information on variability. Table 9 provides the simulation random seeds used in experiment replications.

Table 9: Simulation Random Seeds

FLIGHT	RANDOM SEEDS
1	107, 337, 601, 787, 929
2	821, 1409, 8803, 6703, 7159
3	79043, 99431, 39097, 149, 30977

Full factorial for this experiment consists of 45 experiments. This number of experiments provides the appropriate amount of data to statistically validate research goals and objectives. Table 10 provides a breakdown of the number of experiments performed. There are three mobility trace files that contain flight statistics such as latitude, longitude, and altitude. Also, there are three antenna models to evaluate how the level of detail of an antenna radiation pattern impact simulation model results.

Table 10: Factorial Breakdown

FACTORS	LEVEL	NUMBER
UAV Mobility	Flight Path #1, Flight Path #2, Flight Path #3	3
Antenna Models	Setup #1, Setup #2, Isotropic Antenna	3
Number of Replications	Random Seeds	5
Total Experiments	3*3*5	45

3.12. Methodology Summary

This study answers the primary question: how to accurately characterize the UAV network behavior that is impacted by node mobility, RF propagation, antenna gain, and transmission range. This characterization provides a basis for developing and validating a realistic UAV simulation model. This experiment provides ample results to provide an empirical comparison, following a systematic approach for conducting a performance analysis study. All aspects of the UAV characterization and experimental design were presented, along with simulation model verification and validation.

IV Results and Discussion

4.1. Chapter Overview

This chapter presents the results and analysis on the performance metrics collected from the UAV network simulation characterization developed within this study. Section 4.2 describes validation of the simulation model presented in this research. Section 4.3 discusses the general observations related to the experiment results. Section 4.4 explains the statistical analysis techniques used to evaluate simulation performance. Section 4.5 concludes with a summary of the analysis and results.

4.2. Experiment Validation and Verification

Experiment performance metrics are compared to results from a real-world UAV network implementation. The direct comparison of simulation results against actual test flights ensures that the simulation model provides meaningful answers to the research question at hand, as a result expanding the confidence in this study. As explained in Chapter 3 on pages 35 and 36, each node consists of a wireless network adapter and Omni-directional antenna that represents the physical layer link connecting the transmitter and receiver. As expected, the direction in which the transmitter travels and the distance from the transmitter to the receiver are significant factors to the communication link quality. The primary means to investigate this relationship is through receive power measurements, or the receive signal strength indictor (RSSI), recorded at the destination node. RSSI is a common feature built in radios, cell phones, and wireless network adapters to measure the incoming signal. Generally, the higher the RSSI is the stronger the signal. In many cases this measurement can help determine the alignment of a receiving device for the best possible signal reception. Both wireless modems used in this study have this capability.

Establishing a radio link in OPNET depends on factors such as the node altitude for the antennas, transmission signal power, modulation, and frequency. The receiver power stage of the OPNET radio transceiver pipeline computes the received power of the arriving packet's signal (in watts). This attribute is computed by taking into account the initial transmitted power, the path loss, and receiver and transmitter antenna gains. Received power is calculated by OPNET using:

$$Rcvd\_Power = in\_band\_tx\_power \times tx\_ant\_gain \times path\_loss \times rx\_ant\_gain \qquad (5)$$

where *in_band_tx_power* is the amount of in-band transmitter power, *tx_ant_gain* is the transmitter antenna gain which is calculated by examining the vector between the transmitter and receiver, *path_loss* is computed as a function of wavelength and propagation distance, while *rx_ant_gain* is the receiver antenna gain which is calculated using the same technique as the transmitter antenna gain model, except that the receiver-related attributes are accessed. This study uses the receiver power metric results from the simulation runs to compare against the RSSI data collected from actual test flights as the method to validate the accuracy of the UAV simulation model herein. Output statements from certain phases of the OPNET radio transceiver pipeline are used to support simulation validation. Parameters recorded from these statements are compared against the real-world network representation, consequently, providing evidence that the simulation model is statistically equivalent.

The transmitter node defined in this simulation model follows a predefined trajectory file. The trajectory file consists of traversal-time values and a set of six-dimensional (latitude, longitude, altitude, roll, pitch, and yaw) coordinates that define the UAV's flight path. The procedure for creating flight paths for this study consists of inputting flights coordinates into an ASCII text file with a .trj extension and assigning the file to the UAV node using the "trajectory" attribute in OPNET. Appendix A contains the MATLAB code necessary to create a trajectory file.

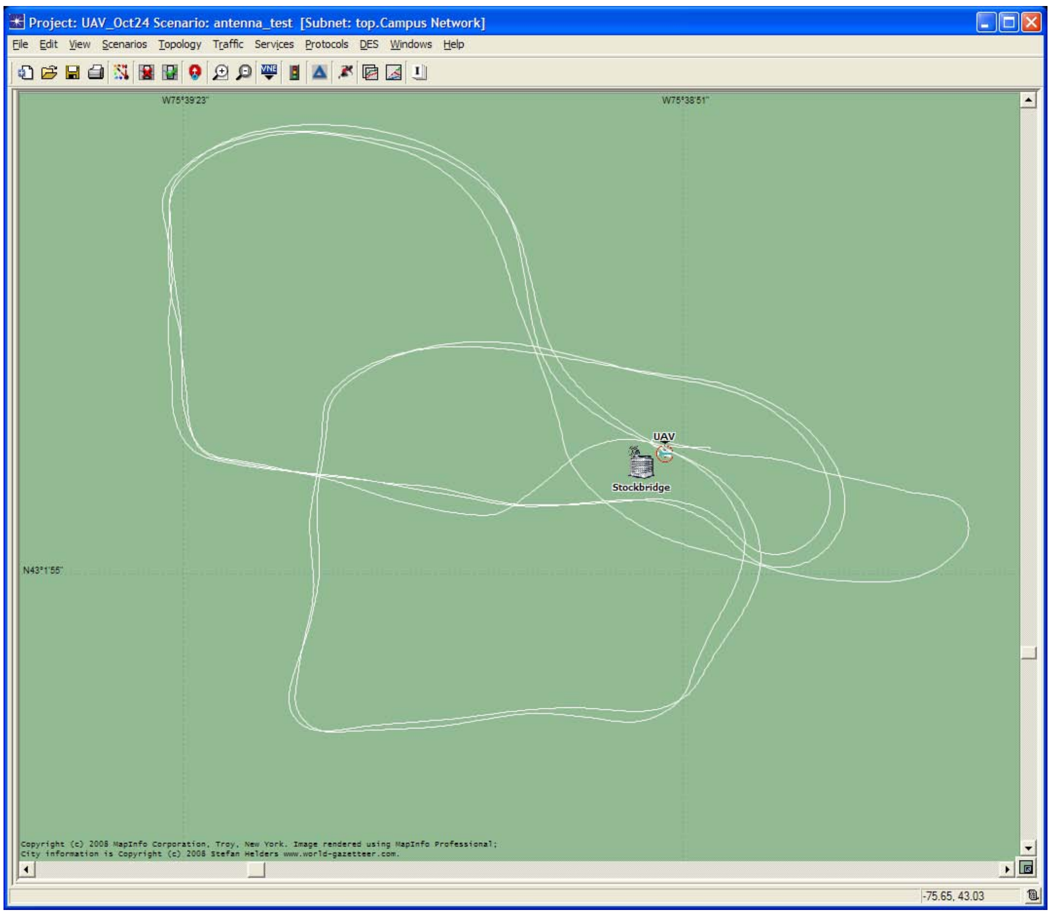


Figure 14: Flight Path Trajectory for Flight #1

Using mobility patterns that most accurately represents real-world system is essential to developing a simulation model that is useful when implemented [14]. Figure

14 illustrates the flight path for Flight #1 of this experiment. Additional flight paths are included in Appendix D.

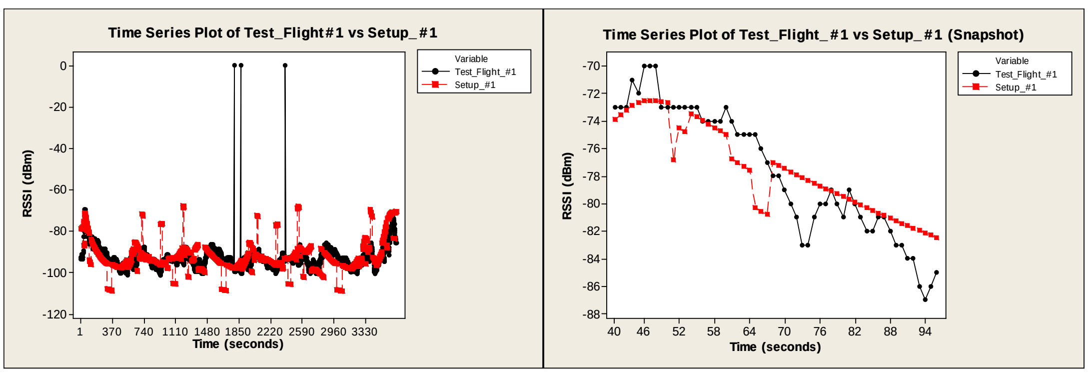
Early pilot tests to evaluate the effects of roll, pitch, and yaw on communication link quality revealed that these flight attributes had no impact on simulation results. Effect is potentially due to our use of Omni-directional antennas in this experiment. We would expect to see these attributes have more of an impact, if directional antennas are used.

4.3. General Observations

To accurately characterize a radio link that existed during real-world test flights is a very ambitious aim due to the various aspects outside the control of our experiment setup. Factors such as interference, noise, terrain, environment conditions, and RSSI variations leads to some expected variance from the real-world link recorded.

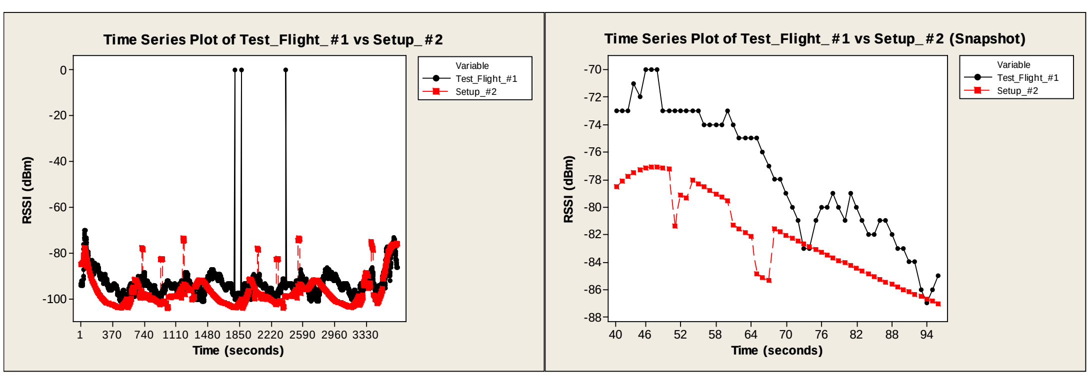
4.3.1. RSSI Observations

Recently, there have been a number of studies [41, 42] investigating the viability of using RSSI data as a means of deriving localization of a transmitting node. In this study, RSSI data is used in conjunction with node positional data to tune the simulation model to resemble the real-world network. Figures 15, 16, and 17 are a set of time series charts from test_flight_#1 that show the visual difference between the RSSI values of the simulation model using different antenna configurations. In general, the time series charts show that the antenna pattern has a significant impact on the recorded RSSI values. Selecting the correct level of detail for an antenna pattern must be well thought out by the network researcher. Figure 17 illustrates how too little detail can produce misleading results. The RSSI values in Figure 17 are approximately 20 dBm stronger than the actual test flight. In contrast, Figure 15 shows that the simulation model was not able to “fully characterize” the actual test flight, but a strong correlation between the actual flight and simulation model was achieved. It was observed that as the antenna model was fine-tuned to resemble reality, there was an increase in the occurrence of outliners in the model. This effect was caused by not having the actual transmitter and receiver antenna radiation patterns available, just a general description was provided. Unfortunately, solving this problem requires complicated antenna engineering, which is outside the scope of this study. Supporting graphs for Flight #2 and #3 are included in Appendix C.



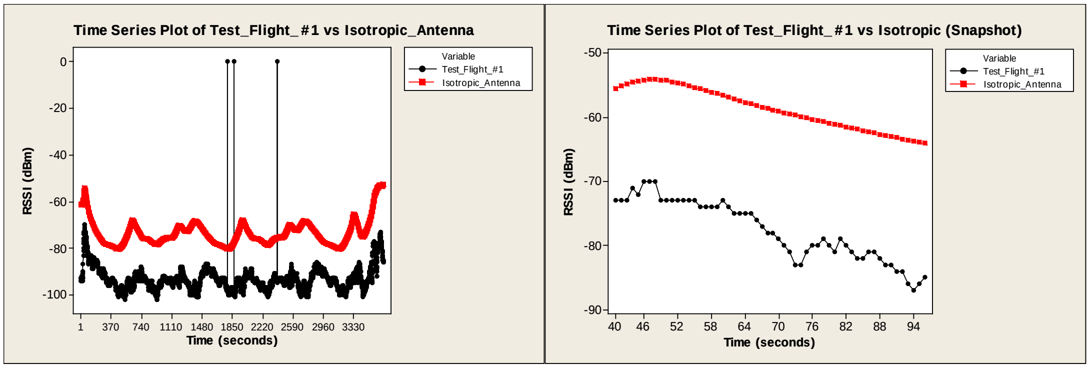
Entire Flight Snapshot in time

Figure 15: Comparison of RSSI values for Flight #1 vs Antenna setup #1



Entire Flight Snapshot in time

Figure 16: Comparison of RSSI values for Flight #1 vs Antenna setup #2



Entire Flight Snapshot in time

Figure 17: Comparison of RSSI values for Flight #1 vs Isotropic Antenna

4.3.2. Throughput Observations

This study shows that increasing the level of fidelity of the antenna radiation pattern also enhances the accuracy of throughput calculation produced by our network simulation model. Figures 18, 19, and 20 show the throughput performance comparison between Flight #1 and the three antenna configuration used in this study. Overall, Antenna setup #1 performed closer to the actual system. As shown in Figure 14, too little detail yields unusable results that cannot be used to answer the research question at hand. In each case, the simulation results shown in Figures 18, 19, and 20 does not exhibit the throughput variability comparable to those generated by the real-world test flight. These results indicate actual model use is dependent on much more than accurately modeling mobility, antenna patterns, and signal strength. This could be attributed to our inability to characterize several key aspects of the test flight. For instance, aspects such as RSSI variability, radio variability, and environmental factors could not be reproduced. Efforts to reproduce these aspects are outside this phase of our research.

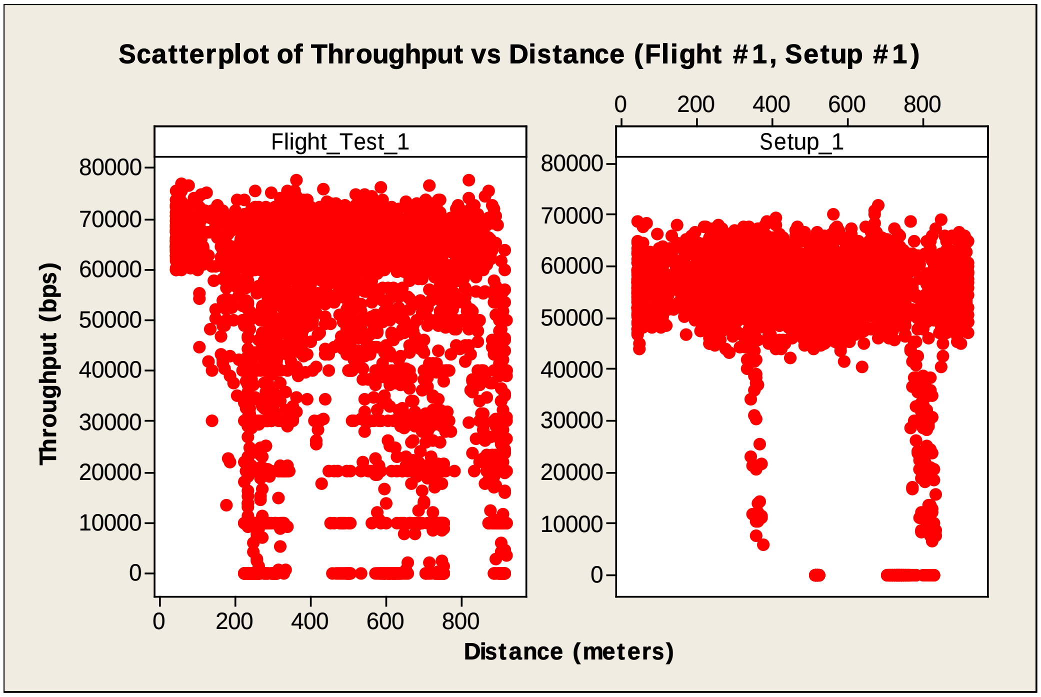


Figure 18: Scatterplot of Flight #1 vs Setup #1

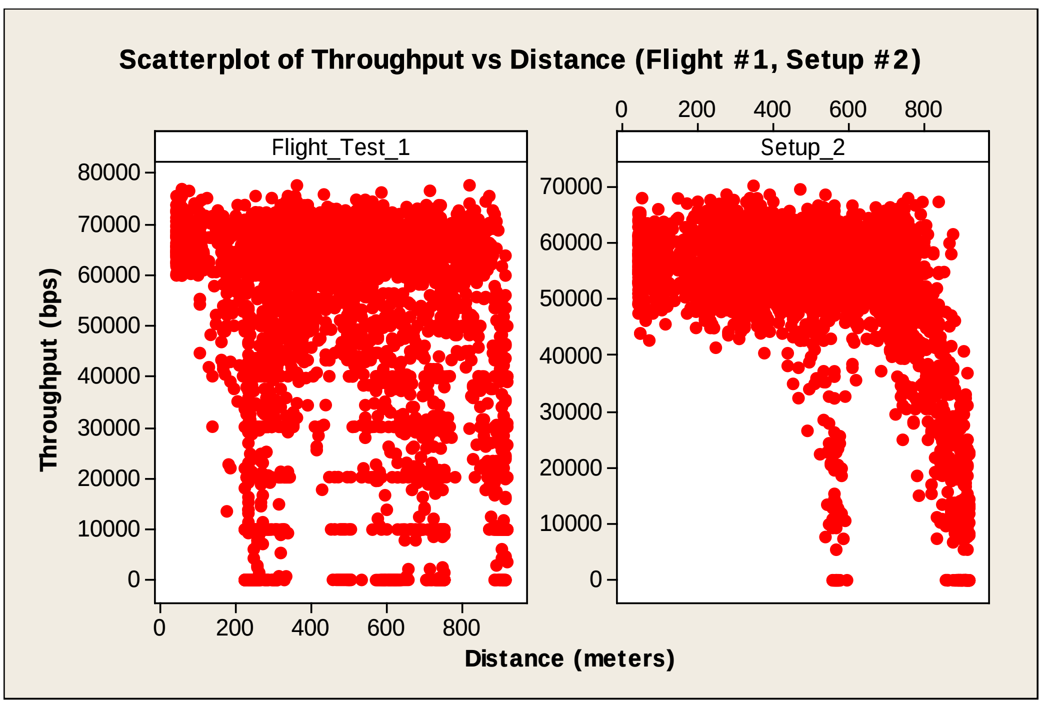


Figure 19: Scatterplot of Flight #1 vs Setup #2

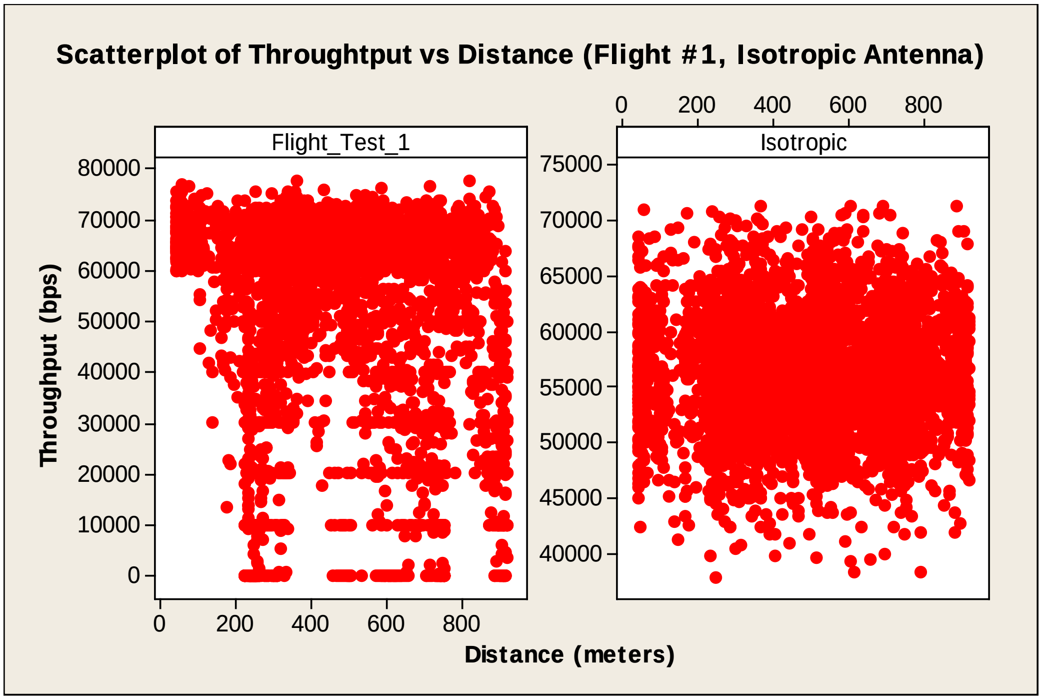


Figure 20: Scatterplot of Flight #1 vs Isotropic Antenna

The authors in [41] pointed out the limitations to using commodity hardware to capture RSSI measurement. They encountered the following limitations that they were able to work around to some degree, such as: non-linearities in RSSI measurements; invalid RSSI values; missing RSSI values in deep fades; and a lack of foreign RF interference characterization. The above limitations are certainly factors that may impact the results attained in our research. They [41] also stated that while a simulator can replay a captured channel trace, it can only do so at a very coarse timescale and with far less fidelity than a physical layer emulator. An unintended observation from our research was the inability to replicate the fine fidelity required to fully replicate the physical layer in a simulation environment. Therefore, the research in our study was only able to observe a similar trend or performance as the real-world system, and not to fully replicate the system under evaluation.

4.3.3. Distance Observations

Wireless communication is a broadcast technology and depends on dynamically changing parameters, such as distance to evaluate the possible connectivity between a transmitter and receiver. OPNET use the distances between nodes to compute link effects such as propagation delay, interference, and received power levels. The transceiver pipeline evaluates the possible connectivity between the receiver and transmitter for each packet transmission. The position of the nodes is a significant factor in a establishing a radio link. The transceiver pipeline calculates whether the transmitter node has direct line-of-sight to the receiver node. If the earth surface or some other object is between the two nodes, then the nodes are said to be occluded and the link computation is discontinued. If there are no obstructions between the nodes, then the link computation continues, and a radio link is possible. OPNET also models the weakening of the radio signal as it propagates from the source site. It is assumed that the path loss is directly related to the reciprocal of the distance squared.

Again, it is immediately obvious from Figures 21, 22, and 23 that the simulation model's RSSI values do not demonstrate the same variability as the real-world test flight. However, these figures illustrate how the simulation model behaviors in a similar matter to the real-world system. Through simulation we were not able to completely replicate the fine fidelity exhibited by the actual test flight, but are able to make general inference on the simulation network performance. Figure 21 shows the relationship between antenna setup #1 and the actual test flight again performing more like the system under evaluation, in comparison to the other antenna configurations.

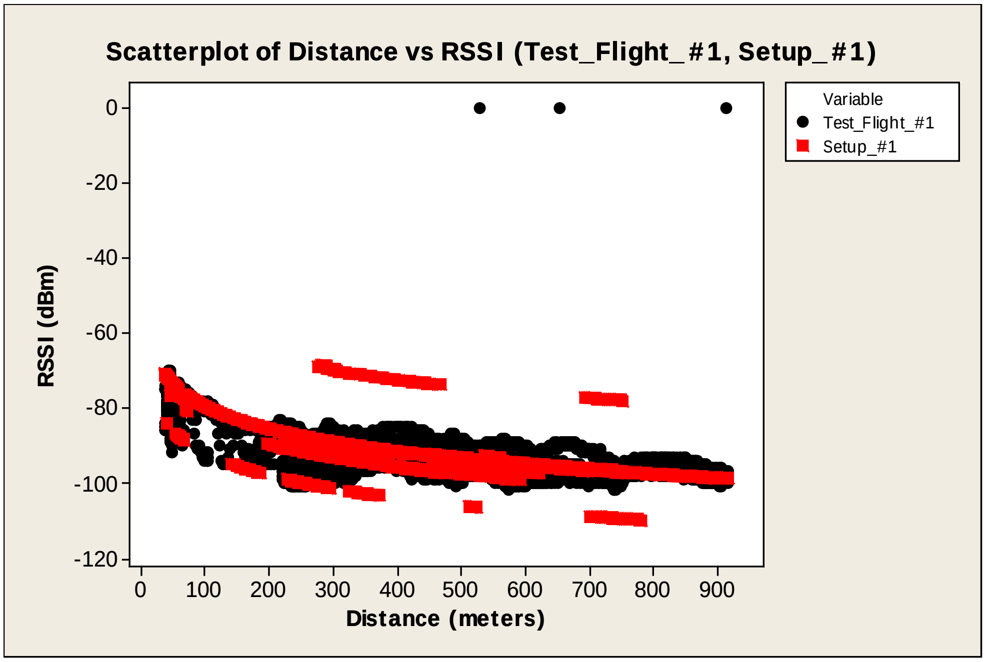


Figure 21: Scatterplot of Distance vs RSSI (Flight #1, Setup #1)

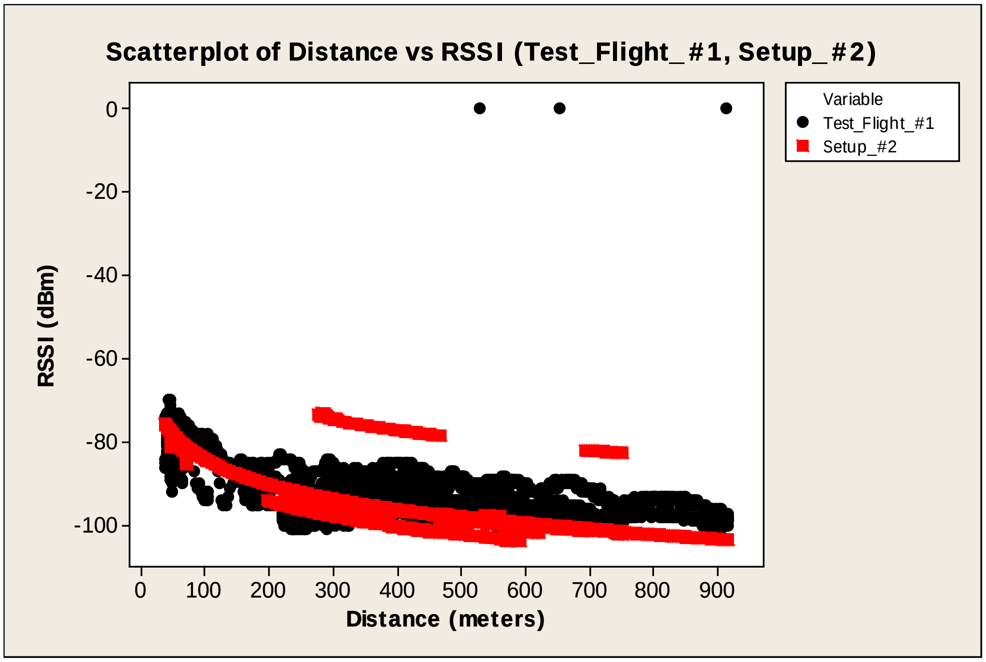


Figure 22: Scatterplot of Distance vs RSSI (Flight #1, Setup #2)

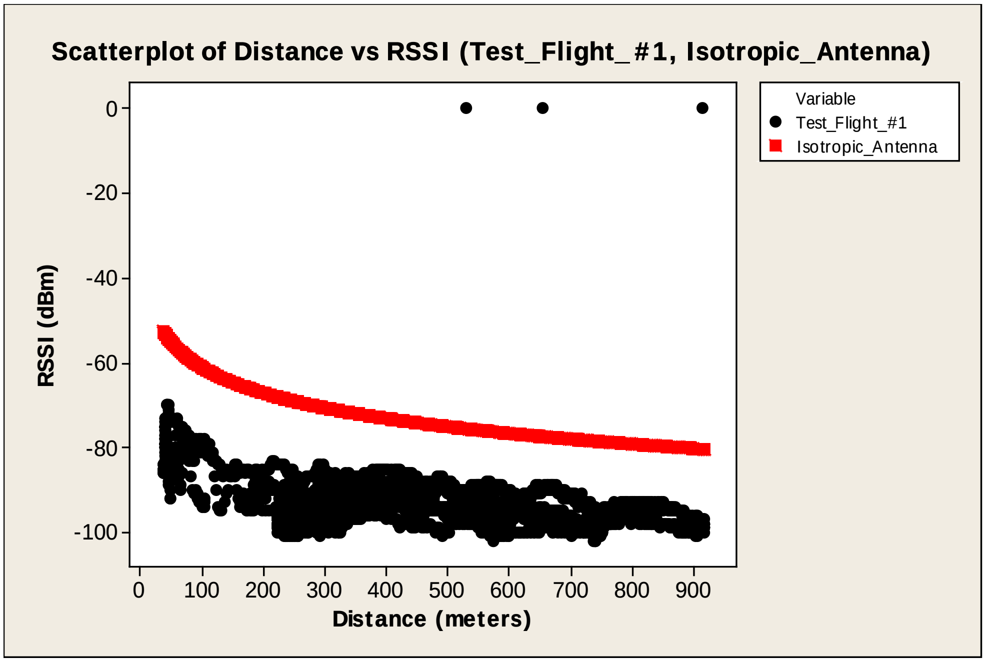


Figure 23: Scatterplot of Distance vs RSSI (Flight #1, Isotropic Antenna)

4.4. Data Analysis

Data analysis consists of results from 45 individual runs evaluating the performance of three flight paths and three antenna configurations. The independent two-sample t-test is used to make inferences about the difference between the means of the real-world test flights and the simulation model. The two-sample t-test assesses whether the means of two systems are statistically different from each other. This technique uses the null hypothesis that the difference between two population means is equal to a hypothesized value and tests it against an alternative hypothesis. Confidence intervals for the mean of differences using the two-sample t-test are calculated using:

$$\text{Confidence interval} = X_1 - X_2 \pm t_{D.F.} \times \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \quad (6)$$

where X_1, s_1, and n_1 are the mean, standard deviation and number of observations for population 1; while X_2, s_2, and n_2 are the mean, standard deviation and number of observations for population 2; t is the t-distribution with degrees of freedom; where α/2 is calculated as:

$$\alpha/2 = \frac{(100 - \%\text{ confidence interval})}{2} \tag{7}$$

and the degrees of freedom (D.F.) is calculated using:

$$\text{D.F.} = \frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\left(s_1^2/n_1\right)^2/(n_1 - 1) + \left(s_2^2/n_2\right)^2/(n_2 - 1)} \tag{8}$$

Confidence intervals of the mean differences that contain zero suggest no difference between two systems. Whereas, for confidence intervals that do not contain zero, there is a statistically significant difference between the two systems.

4.4.1. Flight #1 Analysis

The performance metrics under investigation are RSSI and throughput. Figure 24 is an interval plot of the average RSSI versus antenna radiation pattern configuration. This plot shows the 95% confidence interval centered about the mean for each antenna configuration. Table 11 lists the antenna setup, their means, and the 95% confidence interval, complete statistical results for all three test flights are included in Appendix B. Because there is no overlap of confidence intervals between Flight #1, Setup #2, and the isotropic antenna, the groups are statically different. Because the mean values for Flight #1 and Setup #1 fall within the confidence intervals of each other, suggests that their

RSSI values are not significantly different. Recall that Flight #1 is the real-world flight and Setup #1 is the detailed antenna configuration.

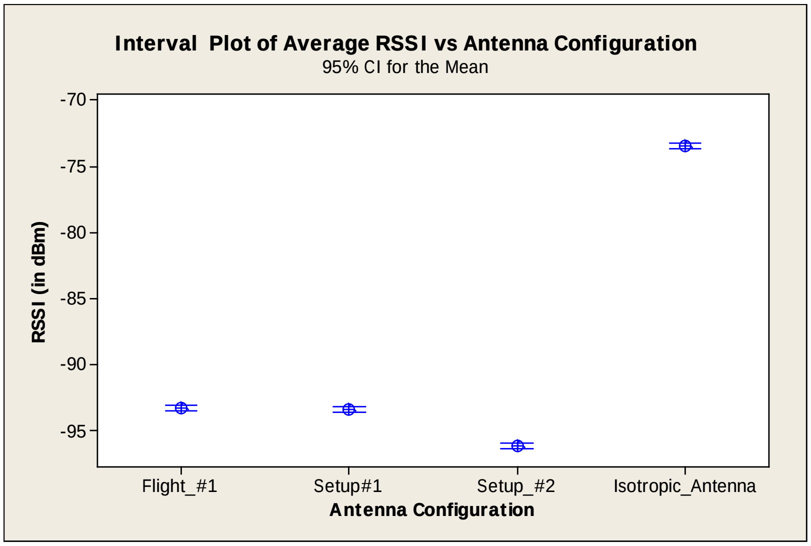


Figure 24: Interval Plot RSSI vs Antenna (Flight #1)

Setup #2's mean average RSSI value (-96.14) is slightly lower than those observed by Flight #1 (-93.31). Whereas the isotropic antenna's mean average RSSI value (-73.44) is much higher. Results of the t-test for Flight #1 and Setup #1 generates a confidence interval of (-0.208, 0.410) which includes zero. Since this confidence interval contains zero, Flight #1 and Setup #1 are not significantly different. The p-value (0.521) for Setup #1 is greater than the alpha value 0.05, which also confirms that there is no evidence of a difference, and the simulation scenario can be considered statistically equivalent.

Table 11: Average RSSI vs Antenna Configuration (95% Confidence Intervals)

Antenna	**Mean (RSSI)**	**Confidence Range**	**p-value**	**Statically equivalent**
1	-93.41	(-0.208, 0.410)	0.521	Y
2	-96.14	(2.555, 3.120)	0.000	N
Isotropic	-73.44	(-20.117, -19.607)	0.000	N

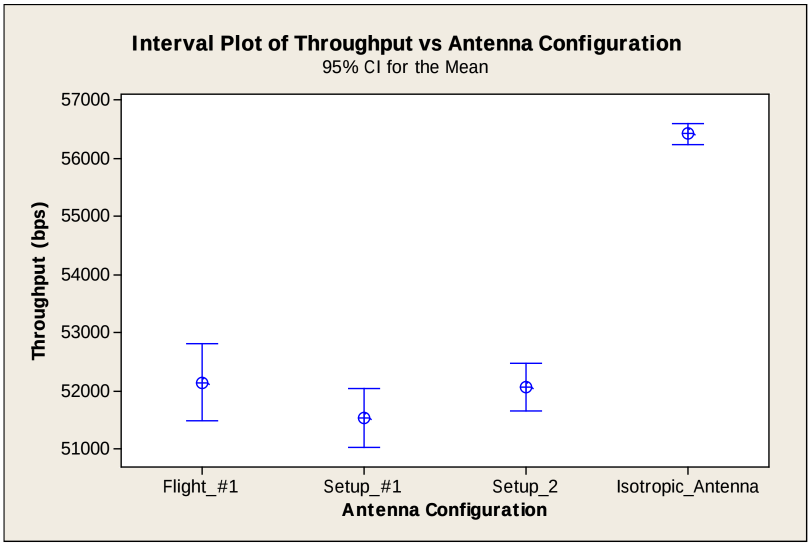


Figure 25: Interval Plot of Throughput vs Antenna (Flight #1)

Figure 25 is an interval plot of the throughput versus the antenna radiation pattern configuration. This plot shows the 95% confidence interval centered about the mean for the antenna configuration. Table 12 lists the antenna setup, their means, and the 95% confidence interval. Since there is no overlap of confidence intervals between Flight #1, and the isotropic antenna, suggest that the groups are statically different. Because the mean values for Flight #1, Setup #1, and Setup #2 fall within the confidence intervals of each other, their throughput values are significantly equivalent.

The isotropic antenna mean throughput (56,423) is much higher than those observed by Flight #1 (52,139), as well as the other groups. This result is caused by the simplistic design of the isotropic antenna. Results of the t-test for Flight #1 and Setup #1 generates a confidence interval of (-223, 1464). The t-test for Flight #1 and Setup #2 generates a confidence interval of (-711, 868). Because these confidence intervals contain zero, Flight #1, Setup #1, and Setup #2 are not significantly different. The p-values for both Setup #1 (0.149) and Setup #2 (0.845) are greater than the alpha value 0.05, which confirms that there is no evidence of a difference, and the simulation scenario can be considered statistically equivalent.

Table 12: Throughput vs Antenna Configuration (95% Confidence Intervals)

Antenna	Mean (bps)	Confidence Range	p-value	Statically equivalent
1	52,518	(-223, 1464)	0.149	Y
2	52,090	(-711, 868)	0.845	Y
Isotropic	56,423	(-4980, -3588)	0.000	N

4.4.2. Flight #2 Analysis

Figure 26 is an interval plot of the average RSSI versus antenna radiation pattern configuration. This plot shows the 95% confidence interval centered about the mean for each antenna configuration. Table 13 lists the antenna setup, their means, and the 95% confidence interval. Because there is no overlap of confidence intervals between Flight #2, Setup #2, and the isotropic antenna, the groups are statistically different. The mean values for Flight #2 and Setup #1 fall within the confidence intervals of each other, suggest that their RSSI values are significantly equivalent. Setup #2's mean average RSSI value (-96.76) is slightly lower than those observed in Flight #2 (-93.91). While the isotropic antenna's mean average RSSI value (-73.69) is much higher. Results of the t-test for Flight #2 and Setup #1 generates a confidence interval of (-0.425, 0.219) which includes zero. Since this confidence interval contains zero, Flight #1 and Setup #1 are not significantly different. The p-value (0.530) for Setup #1 is greater than the alpha value 0.05, which also confirms that there is no evidence of a difference, and the simulation scenario can be considered statistically equivalent.

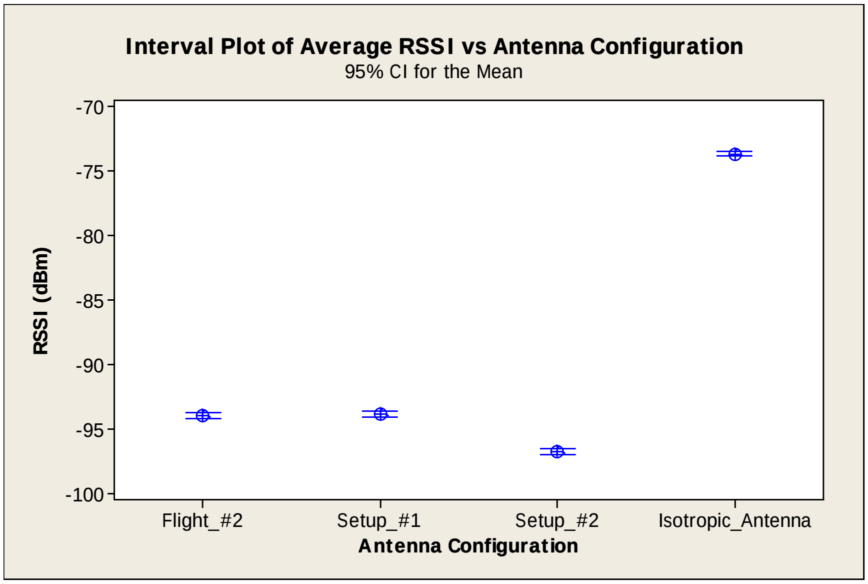


Figure 26: Interval Plot of RSSI vs Antenna (Flight #2)

Table 13: Average RSSI vs Antenna Configuration (95% Confidence Intervals)

Antenna	**Mean (RSSI)**	**Confidence Range**	**p-value**	**Statically equivalent**
1	-93.41	(-0.425, 0.219)	0.530	Y
2	-96.76	(2.543, 3.153)	0.000	N
Isotropic	-73.69	(-20.527, -19.917)	0.000	N

Figure 27 is an interval plot of the throughput versus the antenna radiation pattern configuration. This plot shows the 95% confidence interval centered about the mean for the antenna configuration. Table 14 lists the antenna setup, their means, and the 95% confidence interval. Since there is no overlap of confidence intervals between Flight #2, Setup #2, and the isotropic antenna, the groups are statically different. Because the mean values for Flight #2, and Setup #1 fall within the confidence intervals of each other, their throughput values are not significantly different.

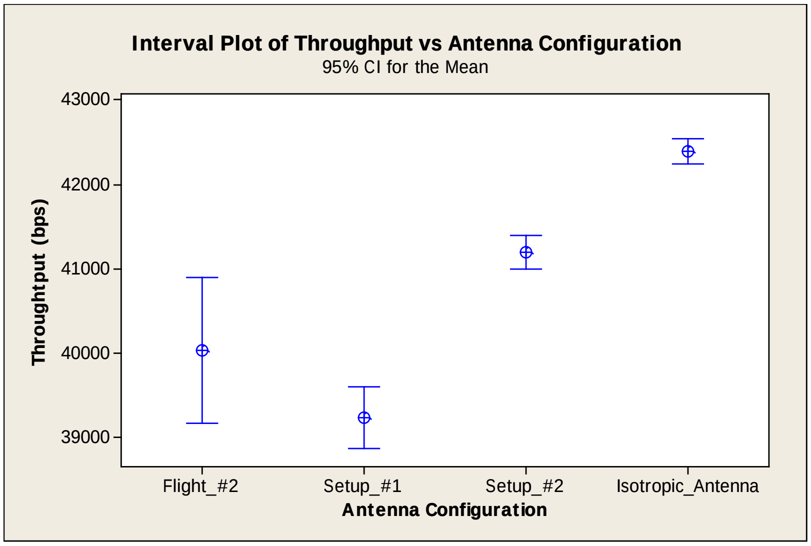


Figure 27: Throughput vs Antenna (Flight #2)

The isotropic antenna mean throughput (42,385) is slightly higher than those observed by Flight #2 (40,030), as well as the other groups. From our observation, this result is caused by the simplistic design of the isotropic antenna. Results of the t-test for Flight #2 and Setup #2 generates a confidence interval of (-2047, -276), thus suggesting the two systems are significantly different. The t-test for Flight #2 and Setup #1 generates a confidence interval of (-144, 1732). Since this confidence intervals contain zero, Flight #2 and Setup #1 are not significantly different. The p-value for Setup #1 (0.097) is greater than the alpha value 0.05, which also confirms that there is no evidence of a difference, and the simulation scenario can be considered statistically equivalent.

Table 14: Throughput vs Antenna Configuration (95% Confidence Intervals)

Antenna	**Mean (bps)**	**Confidence Range**	**p-value**	**Statically equivalent**
1	39,236	(-144, 1732)	0.097	Y
2	41,191	(-2047, -276)	0.010	N
Isotropic	42,385	(-3231, -1479)	0.000	N

4.4.3. Flight #3 Analysis

Figure 28 is an interval plot of the average RSSI versus antenna radiation pattern configuration. This plot shows the 95% confidence interval centered about the mean for each antenna configuration. Table 15 lists the antenna setup, their means, and the 95% confidence interval. Since there is no overlap of confidence intervals between Flight #3, Setup #1, Setup #2, and the isotropic antenna, the groups are statistically different.

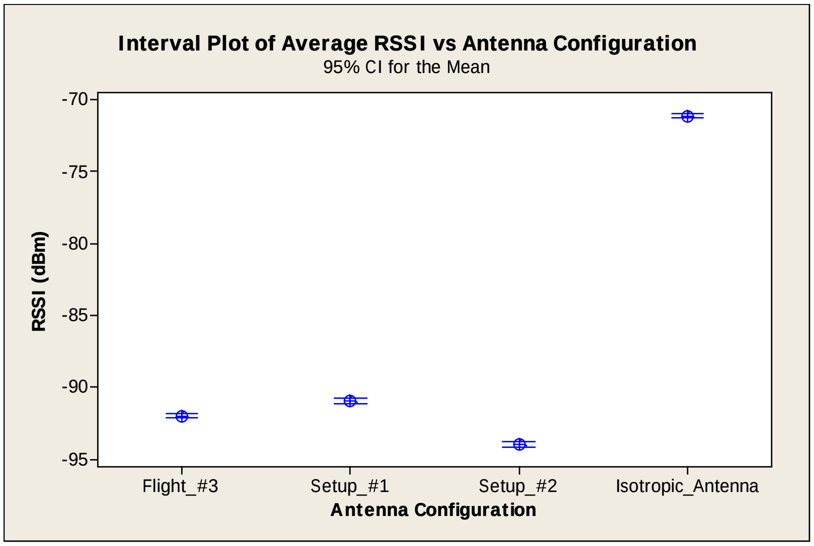


Figure 28: Interval Plot of RSSI vs Antenna (Flight #3)

Setup #1's mean average value (-90.95) is slightly higher than those observed in Flight #3. Setup #2 mean average RSSI value (-93.99) is slightly lower than those observed by Flight #3 (-92.02). Whereas the isotropic antenna's mean average RSSI value (-71.09) is much lower. Results of the t-test for Flight #3 and Setup #1 generates a confidence interval of (-1.366, -0.803), thus not including zero. Whereas, results of the t-test for Flight #3 and Setup #2 generates a confidence interval of (1.727, 2.224), thus not including zero. Where, results of the t-test for Flight #3 and the isotropic antenna generates a confidence interval of (-21.159, -20.706), thus not including zero. Since none of these confidence intervals contains zero, Flight #3 is significantly different from all the groups, and cannot be successfully simulated within our current model.

Table 15: Average RSSI vs Antenna Configuration (95% Confidence Intervals)

Antenna	Mean (RSSI)	Confidence Range	p-value	Statically equivalent
1	-90.95	(-1.366, -0.803)	0.000	N
2	-93.99	(1.727, 2.224)	0.000	N
Isotropic	-71.09	(-29.159, -20.706)	0.000	N

Figure 29 is an interval plot of the throughput versus the antenna radiation pattern configuration. This plot shows the 95% confidence interval centered about the mean for the antenna configuration. Table 16 lists the antenna setup, their means, and the 95% confidence interval. Since there is no overlap of confidence intervals between Flight #3, Setup #2, and the isotropic antenna, suggest that the groups are statistically different. Because the mean values for Flight #3, and Setup #1 fall within the confidence intervals of each other, their throughput values are significantly equivalent.

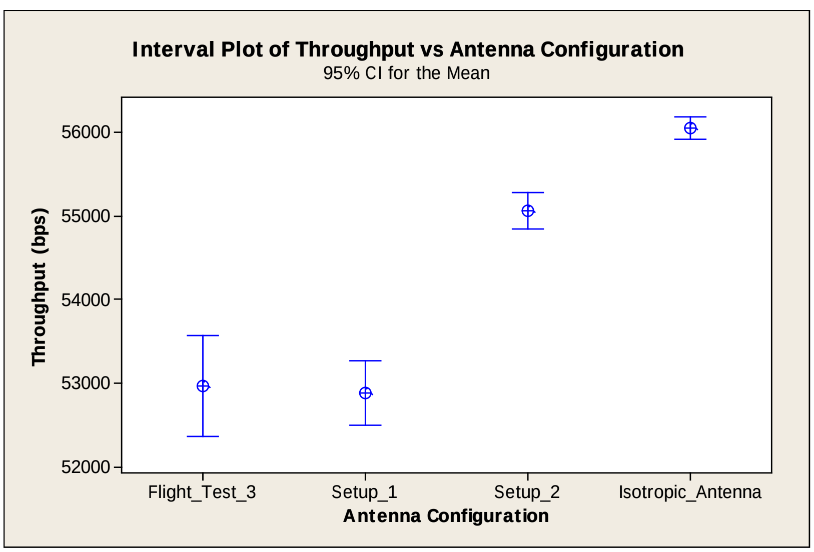


Figure 29: Interval Plot Throughput vs Antenna (Flight #3)

The isotropic antenna mean throughput (56,050) is much higher than those observed by Flight #3 (52,959), as well as the other groups. Again, this result is caused by the simplistic design of the isotropic antenna. Results of the t-test for Flight #3 and Setup #1 generates a confidence interval of (-632, 791). Since this confidence interval contains zero, these systems are not significantly different. The p-value (0.826) for Setup #1 is greater than the alpha value 0.05, which also confirms that there is no evidence of a difference, and the simulation scenario can be considered statistically equivalent. The t-test for Flight #3 and Setup #2 generates a confidence interval of (-2739, -1461). Because this confidence interval does not contain zero, Flight #3, and Setup #2 are significantly different, and cannot be considered statistically equivalent.

Table 16: Throughput vs Antenna Configuration (95% Confidence Intervals)

Antenna	Mean (bps)	Confidence Range	p-value	Statically equivalent
1	52,880	(-632, 791)	0.826	Y
2	55,059	(-2739, -1461)	0.000	N
Isotropic	56,050	(-3704, -2477)	0.000	N

4.4.4. Data Excluded from Analysis

Due to the real-world test-bed data collection method performed by the research sponsor, the following simulation performance metrics could not be validated during this experimentation phase: error rate, SNR, and dropped packets. The test-bed is limited to recording the number of good blocks received between bad blocks. This collection approach is not comparable to the approach OPNET uses to record these measurements.

4.5. Summary of Analysis and Results

The major goals of this study were to develop a simulation network model by using the best simulation practices while providing evidence that model level of detail and node mobility has a significant impact on simulation results. Network research should put considerable thought in how one designs the simulation model physical layer. Too little design will provide misleading results, while attempting to incorporate too much detail can be too time consuming and costly. Through following a systemic approach we were able to demonstrate that the antenna model with the greatest level of detail (Setup #1) strongly correlates to real-world test flights in two of the three flight test under evaluation in this study. As we have noted, there were some instances in the network simulation that did not match the test-bed flights. Preston et al. [23] encountered similar results in their enhanced OPNET models. They recommended addressing these inconsistencies by incorporating an accurate antenna pattern from the actual flying platform. Recall, a general antenna description was only available at the time of this study.

This chapter covered the validation of the network simulation model in this study, as well as the data observation and analysis to explain how network simulation result relates to reality. The two-sample t-test was used to statistically validate our network simulation model's accuracy.

V Conclusions and Recommendations

5.1. Chapter Overview

This chapter concludes the documentation of the research performed. Section 5.2 presents a restatement of research goals. Section 5.3 presents a summary of the conclusions drawn from the analysis and results. Section 5.4 discusses the significance of this research. Section 5.5 discusses recommendations for further research, and Section 5.6 briefly summarizes this chapter.

5.2. Research Goal

The goal of this research was to accurately characterize the behavior of UAV communication networks by incorporating the effects of antenna radiation patterns, signal interference, and flight mobility, as well as developing a validated simulation model. The underlining physical settings that have a significant impact on UAV simulation model accuracy were identified, and a realistic representation of the network was captured. Consequently, demonstrating that through strict validation techniques, a credible simulation model can be achieved.

5.3. Conclusion of Research

Several conclusions can be drawn from the results and analysis of this research. Through sensitivity analysis of the essential OPNET radio transceiver attributes and development of custom antenna models, we were able to create a realistic network simulation model to provide a means of evaluating the airborne network physical layer link. By incorporating actual flight data into our OPNET model, we were able to compare our captured data results against actual flight observations to verify the accuracy of our model. In all cases the antenna setup with the least level of detail produced behavior not representative of the real-world system, thus providing misleading simulation results. Both RSSI and throughput results observed from the isotropic antenna setup from all flights could mislead researchers into believing that the UAV communication link quality is better than it is actually performing. In contrast, the performance of antenna setup #1 strongly correlated to the real-world test flight in two out of the three test flights investigated in this study. These results demonstrated that the appropriate level of detail must be put into designing the simulation network physical level to avoid misleading simulation results.

5.4. Research Significance

This study developed a verified network model that emulates UAV network behavior during flight, using a leading simulation tool. A flexible modeling and simulation environment was developed to test proposed technologies against realistic mission scenarios. In addition, this study identified the essential significant parameters that impact the simulation network model physical layer. We clearly demonstrated there is an interdependent relationship between the UAV transmission power and distance, channel bandwidth, and antenna radiation pattern. These parameters most impacted our simulation performance. Additionally, this research contributes a validated simulation model to the MANET community.

5.5. Recommendations for Future Research

Further research is warranted into the use of receive strength signal indicator using a wireless model that has been calibrated and evaluated to identify variability caused by hardware and environment factors. In addition, including verified antenna radiation patterns and various network protocols would improve the level of confidence of this model.

5.6. Chapter Summary

This chapter presents the overall conclusions that are drawn from the results. Research significance and goals were discussed; and several recommendations for the future are presented.

Appendix A. MATLAB Trajectory Source Code

```
%OPNET Trajectory File
%This file write raw flight data into an OPNET Trajectory File
%Created on: 10/09/2008
clc; clear;
fid = fopen('Flight#1.txt');

%Read raw flight data into text file
%UAS_data columns
%1 etime-- elapsed time(sec)from UTC time 3
%2 qGPS-- quality of PS time from 4
%3 lat-- latitude (deg) from 5-6
%4 long- longitude (deg)7-8
%5 elev-- elevation(m)9
%6 speed--(kph)10
%7 head-- heading (deg)11
%8 nsat--number of satellites seen by GPS 12
%9 roll-- UAV roll(radians)13
%10 pitch-- UAV pitch (radians)14
%11 Uhead-- UAV heading (radians)15
%12 Utrack-- UAV track (radians)16
%13 RSSI --(dBm)17
%14 pGood-- number of good packets since last data point 18
%15 pBad-- number of bad packets since last data point 19
%16 nByte-- number of  bytes received since last data point 20

Data=textscan(fid,'%s%s%s%f%f%c%f%c%f%f%f%f%f%f%f%f%f%f%f%f%s%f%f%c%f%c
%f%f%f%f%f%f%f%f','delimiter', ',');
fclose(fid);
fid = fopen ('Output.txt', 'wt');

%%% Write to .trj file Headers
fprintf(fid,'Version: 3\n');
fprintf(fid,'Position_Unit: Degrees\n');
fprintf(fid,'Altitude_Unit:     meters\n');
fprintf(fid,'Coordinate_Method: fixed\n');
fprintf(fid,'Altitude_Method: absolute\n');
fprintf(fid,'locale: C\n');
fprintf(fid,'Calendar_Start: unused\n');
fprintf(fid,'Coordinate_Count: %u\n',size(Data{1,1},1));
fprintf(fid,'# X Position        ,Y Position          ,Altitude
');
fprintf(fid,'   ,Traverse Time       ,Wait Time           ,Pitch
');
fprintf(fid,'    ,Yaw                 ,Roll                \n');

%Write flight data into trajectory file
lat = Data{1,5}/(60*100000);
lat_direction = Data{1,6};
long = Data{1,7}/(60*100000);
long_direction = Data{1,8};
Alt = Data{1,9}/10;
roll = Data{1,13}/1000;
```

```
pitch = Data{1,14}/1000;
yaw = Data{1,15}/1000;
RSSI = Data{1,17};
good_packets = Data{1,18};
bad_packets = Data{1,19};
bytes_received = Data{1,20};
total = size(Data{1,1},1);
for n = 1:total;
    if strcmp('N', lat_direction(n))
        lat(n) = 1 * lat(n);
    else
        lat(n) = -1 *lat(n);
    end
    if strcmp('E', long_direction(n))
        long(n) = 1 * long(n);
    else
        long(n) = -1 *long(n);
    end
end

for count = 1:total;
   fprintf(fid,'%.9f        ,%.9f', long(count), lat(count));
   fprintf(fid,'        ,%.2f              ,0h0m1.0s', Alt(count));
   fprintf(fid,'            ,0h0m0.0s            ,%f', pitch(count));
   fprintf(fid,'        ,%.5f             ,%.5f\n', yaw(count),
roll(count));
end;
fclose (fid);


fid1 = fopen ('packet_summary.txt', 'wt');
fprintf(fid1,'RSSI        ,# of Good_packets          ,# of Bad_packets
,Received_packets\n');

for count = 1:total;
fprintf(fid1,',%d             ,%d', RSSI(count), good_packets(count));
fprintf(fid1,'                          ,%d                       ,%d\n',
bad_packets(count), bytes_received(count));
end;

fclose (fid1);
%Program End
```

Appendix B. Supporting Data

This appendix provides data to support the analysis of this study. The two-sample t-test results for all flight are contained in this appendix.

B.1. Flight #1 Analysis

Two-Sample T-Test and CI: Flight #1, Setup #1

```
                        N    Mean  StDev  SE Mean
Flight #1            3697  -93.31   5.52    0.091
Custom_Antenna_1     3697  -93.41   7.84     0.13

Difference = mu (Flight #1) - mu (Setup #1)
Estimate for difference:  0.101
95% CI for difference:  (-0.208, 0.410)
T-Test of difference = 0 (vs not =): T-Value = 0.64  P-Value = 0.521  DF = 6633
```

Two-Sample T-Test and CI: Flight #1, Setup #2

```
                        N    Mean  StDev  SE Mean
Flight #1            3697  -93.31   5.52    0.091
Custom_Antenna_2     3697  -96.14   6.81     0.11

Difference = mu (Flight #1) - mu (Setup #2)
Estimate for difference:  2.837
95% CI for difference:  (2.555, 3.120)
T-Test of difference = 0 (vs not =): T-Value = 19.68  P-Value = 0.000  DF =
     7086
```

Two-Sample T-Test and CI: Flight #1, Isotropic Antenna

```
                        N    Mean  StDev  SE Mean
Flight #1            3697  -93.31   5.52    0.091
Isotropic Antenna    3697  -73.44   5.67    0.093

Difference = mu (Flight #1) - mu (Isotropic Antenna)
Estimate for difference:  -19.862
95% CI for difference:  (-20.117, -19.607)
T-Test of difference = 0 (vs not =): T-Value = -152.63  P-Value = 0.000  DF =
     7386
```

Two-Sample T-Test and CI: Flight #1, Setup #1 (Snapshot)

```
                      N    Mean  StDev  SE Mean
Flight #1            56  -77.64   4.71     0.63
Setup #1             56  -77.51   3.23     0.43

Difference = mu (Flight #1) - mu (Setup_1)
Estimate for difference:  -0.132
95% CI for difference:  (-1.647, 1.383)
```

T-Test of difference = 0 (vs not =): T-Value = -0.17 P-Value = 0.863 DF = 97

Two-Sample T-Test and CI: Flight #1, Setup #2 (Snapshot)

	N	Mean	StDev	SE Mean
Flight #1	56	-77.64	4.71	0.63
Setup_2	56	-82.09	3.23	0.43

Difference = mu (Flight #1) - mu (Setup #2)
Estimate for difference: 4.445
95% CI for difference: (2.930, 5.960)
T-Test of difference = 0 (vs not =): T-Value = 5.82 P-Value = 0.000 DF = 97

Two-Sample T-Test and CI: Flight #1, Isotropic Antenna (Snapshot)

	N	Mean	StDev	SE Mean
Flight #1	56	-77.64	4.71	0.63
Isotropic Antenna	56	-58.64	3.29	0.44

Difference = mu (Flight #1) - mu (Isotropic Antenna)
Estimate for difference: -19.005
95% CI for difference: (-20.529, -17.482)
T-Test of difference = 0 (vs not =): T-Value = -24.76 P-Value = 0.000 DF = 98

Two-Sample T-Test and CI: Flight #1, Setup #1 (Throughput)

	N	Mean	StDev	SE Mean
Flight #1	3696	52139	20905	344
Setup #1	3696	51518	15710	258

Difference = mu (Flight #1) - mu (Setup #1)
Estimate for difference: 621
95% CI for difference: (-223, 1464)
T-Test of difference = 0 (vs not =): T-Value = 1.44 P-Value = 0.149 DF = 6859

Two-Sample T-Test and CI: Flight #1, Setup #2 (Throughput)

	N	Mean	StDev	SE Mean
Flight #1	3696	52139	20905	344
Setup #2	3696	52060	12734	209

Difference = mu (Flight #1) - mu (Setup #2)
Estimate for difference: 79
95% CI for difference: (-711, 868)
T-Test of difference = 0 (vs not =): T-Value = 0.20 P-Value = 0.845 DF = 610

Two-Sample T-Test and CI: Flight #1, Isotropic Antenna (Throughput)

	N	Mean	StDev	SE Mean
Flight #1	3696	52139	20905	344
Isotropic Antenna	3696	56423	5390	89

Difference = mu (Flight #1) - mu (Isotropic Antenna)
Estimate for difference: -4284

```
95% CI for difference:  (-4980, -3588)
T-Test of difference = 0 (vs not =): T-Value = -12.06  P-Value = 0.000  DF =
     4184
```

B.2. Flight #2 Analysis

Two-Sample T-Test and CI: Flight #2, Setup #1

	N	Mean	StDev	SE Mean
Flight #2	3674	-93.91	7.20	0.12
Setup #1	3674	-93.81	6.87	0.11

```
Difference = mu (Flight #2) - mu (Setup #1)
Estimate for difference:  -0.103
95% CI for difference:  (-0.425, 0.219)
T-Test of difference = 0 (vs not =): T-Value = -0.63  P-Value = 0.530  DF =
     7329
```

Two-Sample T-Test and CI: Flight #2, Setup #2

	N	Mean	StDev	SE Mean
Flight #2	3674	-93.91	7.20	0.12
Setup #2	3674	-96.76	6.08	0.10

```
Difference = mu (Flight #2) - mu (Setup #2)
Estimate for difference:  2.848
95% CI for difference:  (2.543, 3.153)
T-Test of difference = 0 (vs not =): T-Value = 18.32  P-Value = 0.000  DF =
     7143
```

Two-Sample T-Test and CI: Flight #2, Isotropic Antenna

	N	Mean	StDev	SE Mean
Flight #2	3674	-93.91	7.20	0.12
Isotropic Antenna	3674	-73.69	6.10	0.10

```
Difference = mu (Flight #2) - mu (Isotropic Antenna)
Estimate for difference:  -20.222
95% CI for difference:  (-20.527, -19.917)
T-Test of difference = 0 (vs not =): T-Value = -129.87  P-Value = 0.000  DF =
     7150
```

Two-Sample T-Test and CI: Flight #2, Setup #1 (Snapshot)

	N	Mean	StDev	SE Mean
Flight #2	50	-83.50	3.21	0.45
Setup #1	50	-83.92	1.90	0.27

```
Difference = mu (Flight #2) - mu (Setup #1)
Estimate for difference:  0.425
95% CI for difference:  (-0.624, 1.474)
T-Test of difference = 0 (vs not =): T-Value = 0.81  P-Value = 0.423  DF = 79
```

Two-Sample T-Test and CI: Flight #2, Setup #2 (Snapshot)

	N	Mean	StDev	SE Mean
Flight #2	50	-83.50	3.21	0.45
Setup_2	50	-88.81	1.90	0.27

Difference = mu (Flight #2) - mu (Setup #2)
Estimate for difference: 5.306
95% CI for difference: (4.257, 6.355)
T-Test of difference = 0 (vs not =): T-Value = 10.07 P-Value = 0.000 DF = 79

Two-Sample T-Test and CI: Flight #2, Isotropic Antenna (Snapshot)

	N	Mean	StDev	SE Mean
Flight #2	50	-83.50	3.21	0.45
Isotropic Antenna	50	-64.736	0.712	0.10

Difference = mu (Flight #2) - mu (Isotropic Antenna)
Estimate for difference: -18.764
95% CI for difference: (-19.697, -17.832)
T-Test of difference = 0 (vs not =): T-Value = -40.37 P-Value = 0.000 DF = 53

Two-Sample T-Test and CI: Flight #2, Setup #1 (Throughput)

	N	Mean	StDev	SE Mean
Flight #2	3674	40030	26686	440
Setup #1	3674	39236	11331	187

Difference = mu (Flight #2) - mu (Setup #1)
Estimate for difference: 794
95% CI for difference: (-144, 1732)
T-Test of difference = 0 (vs not =): T-Value = 1.66 P-Value = 0.097 DF = 4955

Two-Sample T-Test and CI: Flight #2, Setup #2 (Throughput)

	N	Mean	StDev	SE Mean
Flight #2	3674	40030	26686	440
Setup #2	3674	41191	6058	100

Difference = mu (Flight #2) - mu (Setup_2)
Estimate for difference: -1161
95% CI for difference: (-2047, -276)
T-Test of difference = 0 (vs not =): T-Value = -2.57 P-Value = 0.010 DF = 4050

Two-Sample T-Test and CI: Flight #2, Isotropic Antenna (Throughput)

	N	Mean	StDev	SE Mean
Flight #2	3674	40030	26686	440
Isotropic Antenna	3674	42385	4593	76

Difference = mu (Flight #2) - mu (Isotropic Antenna)
Estimate for difference: -2355

```
95% CI for difference:  (-3231, -1479)
T-Test of difference = 0 (vs not =): T-Value = -5.27  P-Value = 0.000  DF =
     3890
```

B.3. Flight #3 Analysis

Two-Sample T-Test and CI: Flight #3, Setup #1

```
                         N    Mean  StDev  SE Mean
Flight #3             4505  -92.02   5.80    0.086
Setup #1              4505  -90.95   7.04     0.10

Difference = mu (Flight #3) - mu (Setup #1)
Estimate for difference:  -1.069
95% CI for difference:  (-1.336, -0.803)
T-Test of difference = 0 (vs not =): T-Value = -7.87  P-Value = 0.000  DF =
     8688
```

Two-Sample T-Test and CI: Flight #3, Setup #2

```
                      N    Mean  StDev  SE Mean
Flight #3          4505  -92.02   5.80    0.086
Setup #2           4505  -93.99   6.22    0.093

Difference = mu (Flight #3) - mu (Setup #2)
Estimate for difference:  1.975
95% CI for difference:  (1.727, 2.224)
T-Test of difference = 0 (vs not =): T-Value = 15.59  P-Value = 0.000  DF =
     8964
```

Two-Sample T-Test and CI: Flight #3, Isotropic Antenna

```
                      N    Mean  StDev  SE Mean
Flight #3          4505  -92.02   5.80    0.086
Isotropic Antenna  4505  -71.09   5.15    0.077

Difference = mu (Flight #3) - mu (Isotropic Antenna)
Estimate for difference:  -20.933
95% CI for difference:  (-21.159, -20.706)
T-Test of difference = 0 (vs not =): T-Value = -181.16  P-Value = 0.000  DF =
     8884
```

Two-Sample T-Test and CI: Flight #3, Setup #1 (Snapshot)

```
                      N    Mean  StDev  SE Mean
Flight #3            50  -74.96   3.05     0.43
Setup_1              50  -77.45   6.33     0.90

Difference = mu (Flight #3) - mu (Setup #1)
Estimate for difference:  2.490
95% CI for difference:  (0.508, 4.473)
T-Test of difference = 0 (vs not =): T-Value = 2.51  P-Value = 0.015  DF = 70
```

Two-Sample T-Test and CI: Flight #3, Setup #2 (Snapshot)

	N	Mean	StDev	SE Mean
Flight #3	50	-74.96	3.05	0.43
Setup #2	50	-76.820	0.225	0.032

Difference = mu (Flight #3) - mu (Setup #2)
Estimate for difference: 1.860
95% CI for difference: (0.990, 2.729)
T-Test of difference = 0 (vs not =): T-Value = 4.30 P-Value = 0.000 DF = 49

Two-Sample T-Test and CI: Flight #3, Isotropic Antenna (Snapshot)

	N	Mean	StDev	SE Mean
Flight #3	50	-74.96	3.05	0.43
Isotropic Antenna	50	-53.815	0.226	0.032

Difference = mu (Flight #3) - mu (Isotropic Antenna)
Estimate for difference: -21.145
95% CI for difference: (-22.014, -20.275)
T-Test of difference = 0 (vs not =): T-Value = -48.88 P-Value = 0.000 DF = 49

Two-Sample T-Test and CI: Flight #3, Setup #1 (Throughput)

	N	Mean	StDev	SE Mean
Flight #3	4505	52959	20498	305
Setup #1	4505	52880	13156	196

Difference = mu (Flight #3) - mu (Setup #1)
Estimate for difference: 80
95% CI for difference: (-632, 791)
T-Test of difference = 0 (vs not =): T-Value = 0.22 P-Value = 0.826 DF = 7676

Two-Sample T-Test and CI: Flight #3, Setup #2 (Throughput)

	N	Mean	StDev	SE Mean
Flight #3	4505	52959	20498	305
Setup #2	4505	55059	7635	114

Difference = mu (Flight #3) - mu (Setup #2)
Estimate for difference: -2100
95% CI for difference: (-2739, -1461)
T-Test of difference = 0 (vs not =): T-Value = -6.44 P-Value = 0.000 DF =
5730

Two-Sample T-Test and CI: Flight #3, Isotropic Antenna (Throughput)

	N	Mean	StDev	SE Mean
Flight #3	4505	52959	20498	305
Isotropic Antenna	4505	56050	4562	68

Difference = mu (Flight_Test_3) - mu (Isotropic)
Estimate for difference: -3091
95% CI for difference: (-3704, -2477)
T-Test of difference = 0 (vs not =): T-Value = -9.88 P-Value = 0.00 DF =
4949

Appendix C. Supporting Figures

This appendix contains Flight #2 and Flight #3figures to support the analysis of this study. These support discussion in section 4.3.

C.1. Flight #2

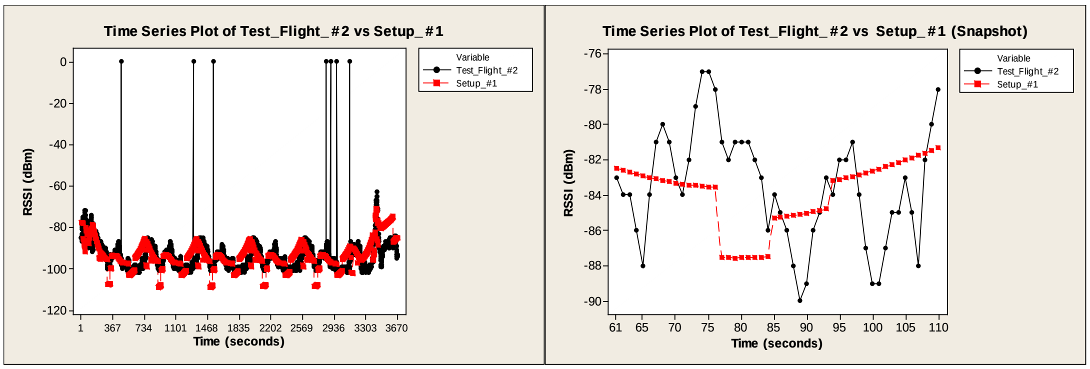


Figure 30: Comparison of RSSI values for Flight #2 vs Antenna setup #1

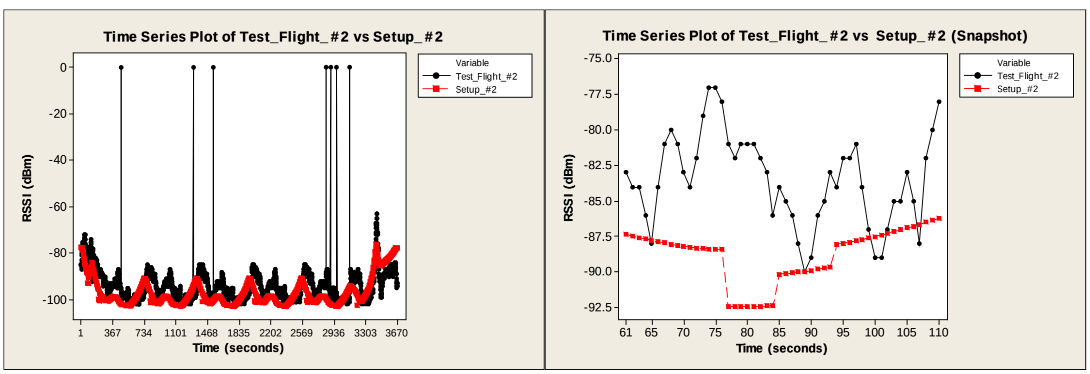


Figure 31: Comparison of RSSI values for Flight #2 vs Antenna setup #1

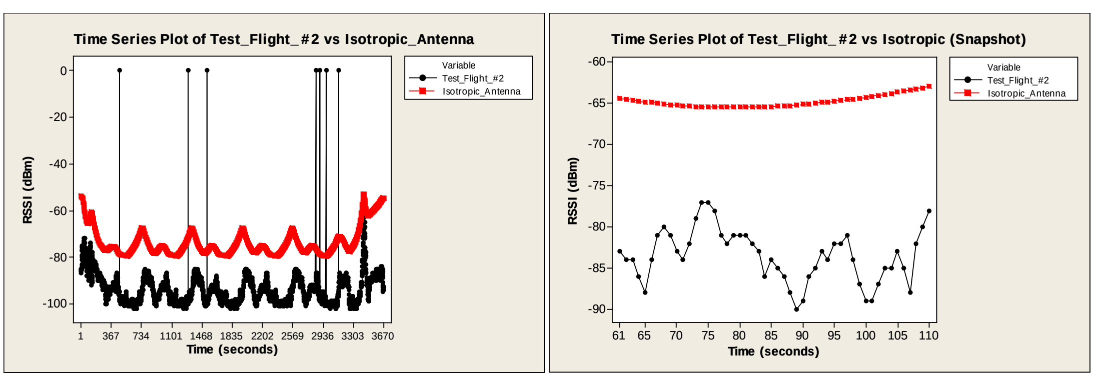


Figure 32: Comparison of RSSI values for Flight #2 vs Isotropic Antenna

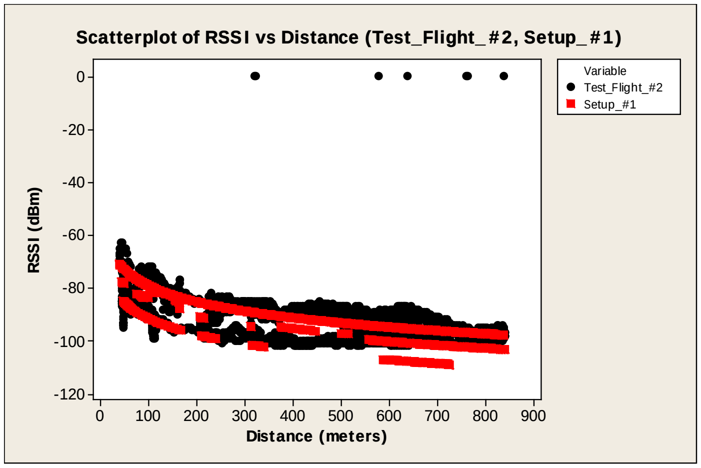


Figure 33: Scatterplot of Distance vs RSSI (Flight #2, Setup #1)

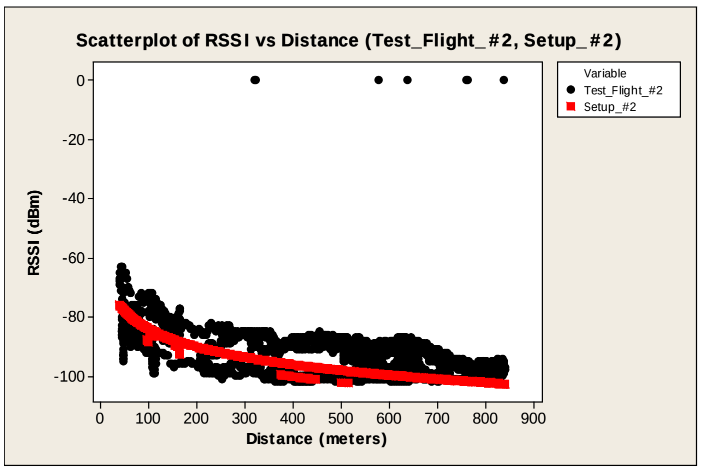


Figure 34: Scatterplot of Distance vs RSSI (Flight #2, Setup #2)

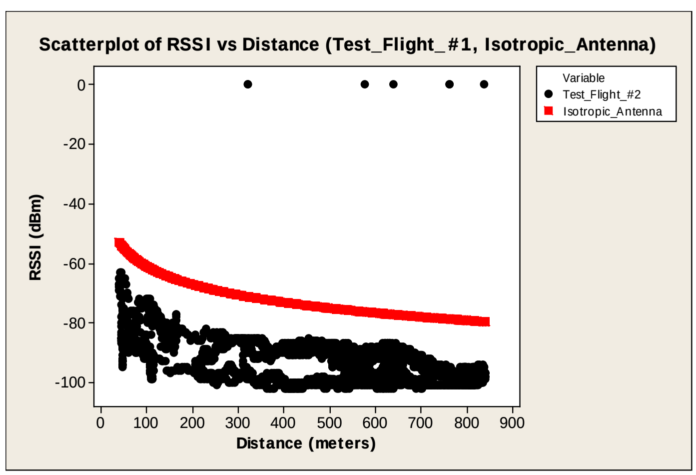


Figure 35: Scatterplot of Distance vs RSSI (Flight #2, Isotropic)

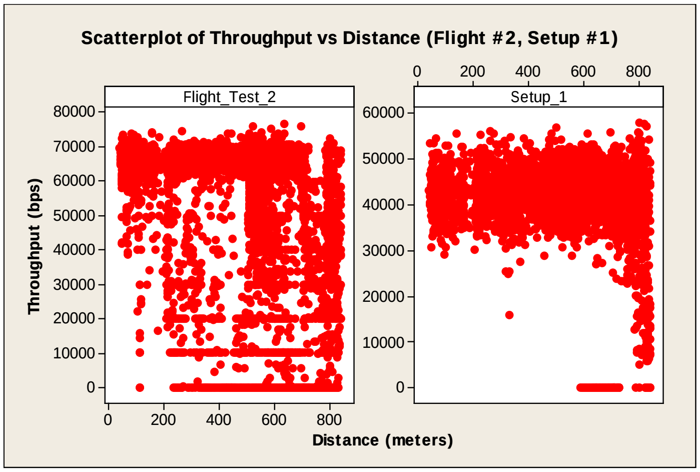


Figure 36: Scatterplot of Flight #2 vs Setup #1

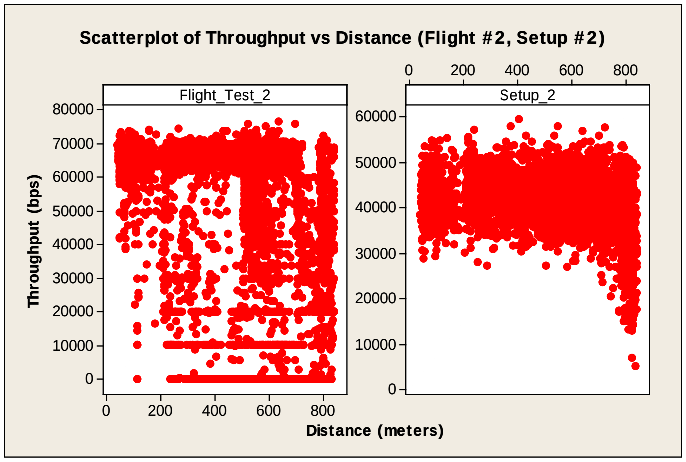


Figure 37: Scatterplot of Flight #2 vs Setup #2

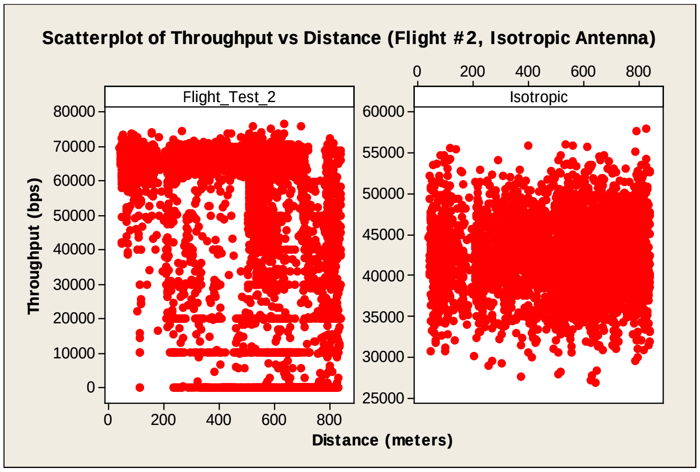


Figure 38: Scatterplot of Flight #2 vs Isotropic

C.2. Flight #3

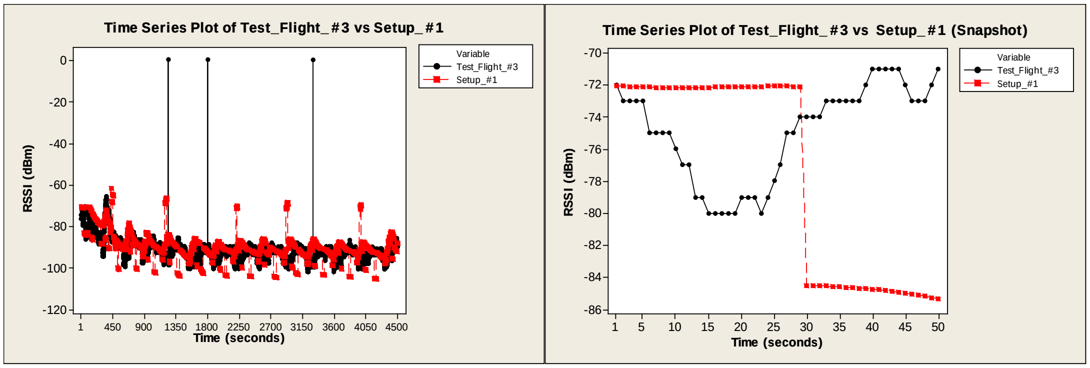


Figure 39: Comparison of RSSI values for Flight #3 vs Setup #1

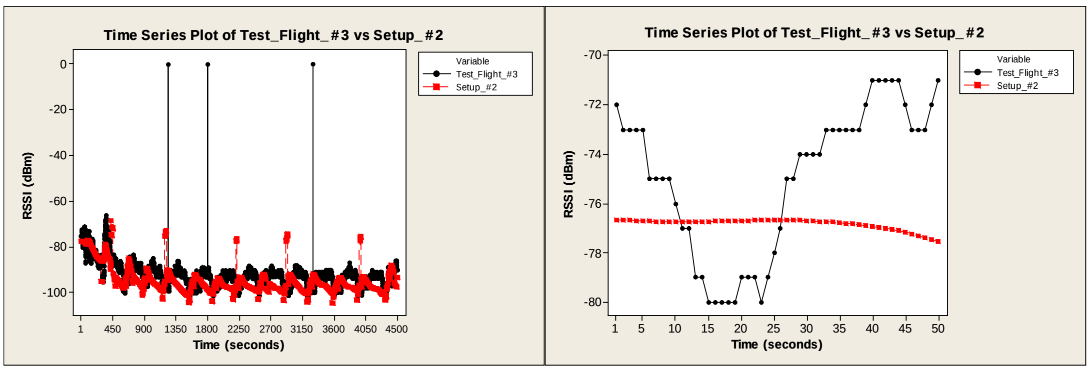


Figure 40: Comparison of RSSI values for Flight #3 vs Setup #2

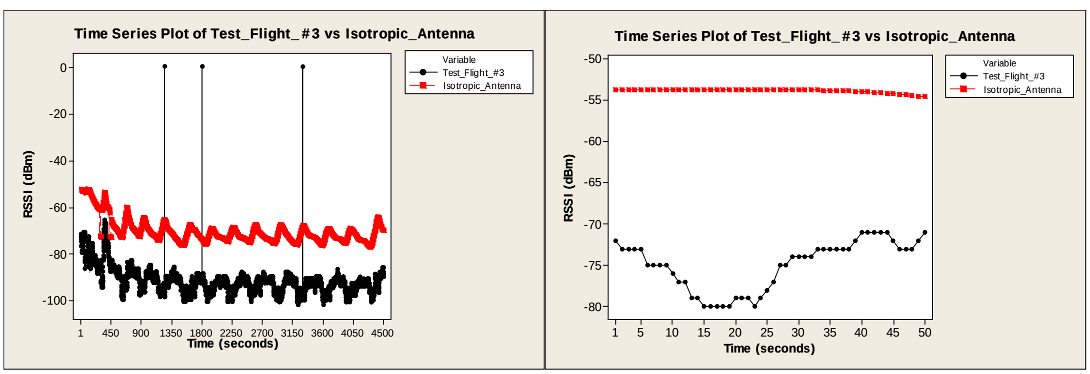


Figure 41: Comparison of RSSI values for Flight #3 vs Isotropic Antenna

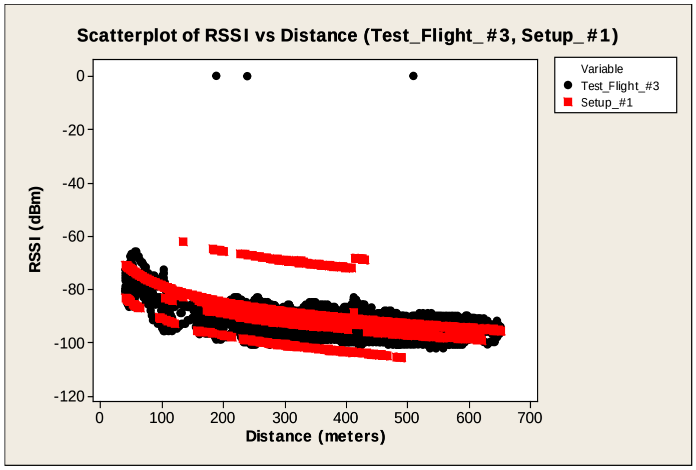


Figure 42: Scatterplot of Distance vs RSSI (Flight #3, Setup #1)

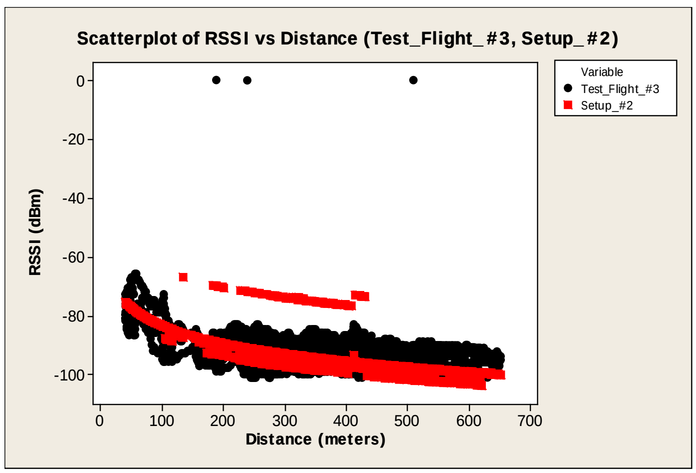


Figure 43: Scatterplot of Distance vs RSSI (Flight #3, Setup #2)

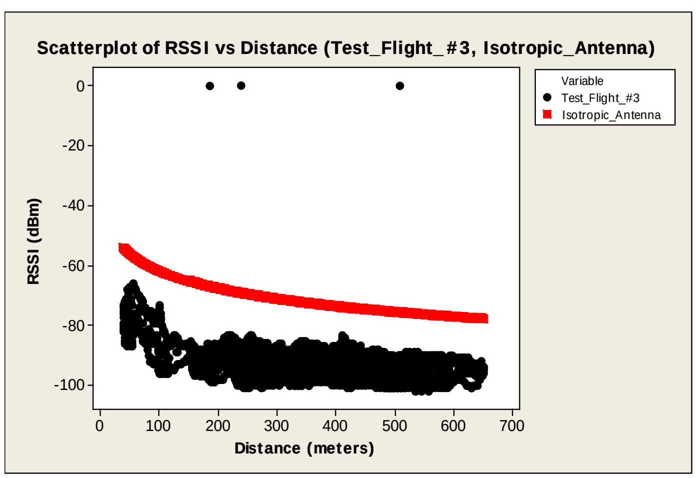


Figure 44: Scatterplot of Distance vs RSSI (Flight #3, Isotropic)

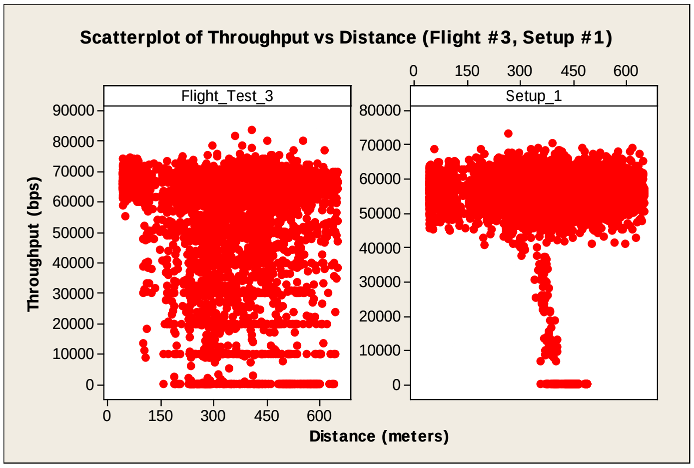


Figure 45: Scatterplot of Flight #3 vs Setup #1

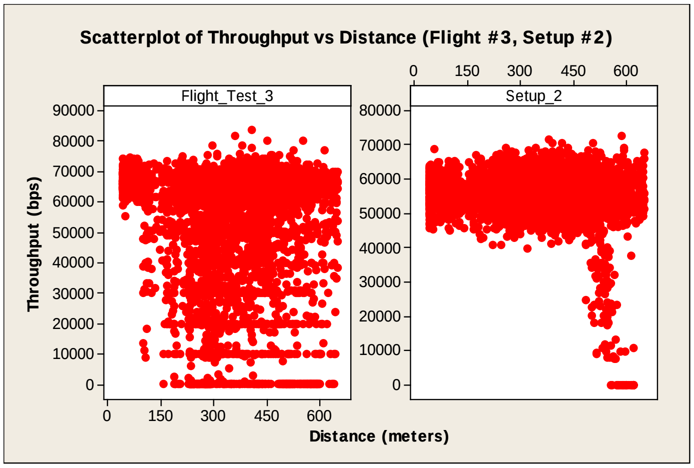


Figure 46: Scatterplot of Flight #3 vs Setup #2

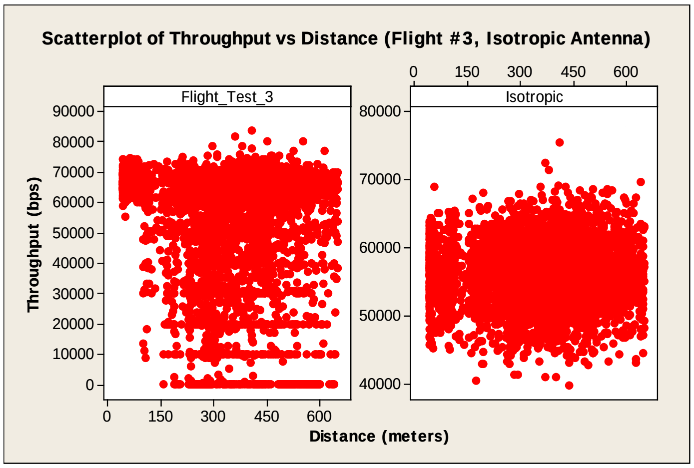


Figure 47: Scatterplot of Flight #3 vs Isotropic

Appendix D. Flight Paths

This appendix contains the flight path trajectory graphs for flight #2 and flight #3.

D.1. Flight #2

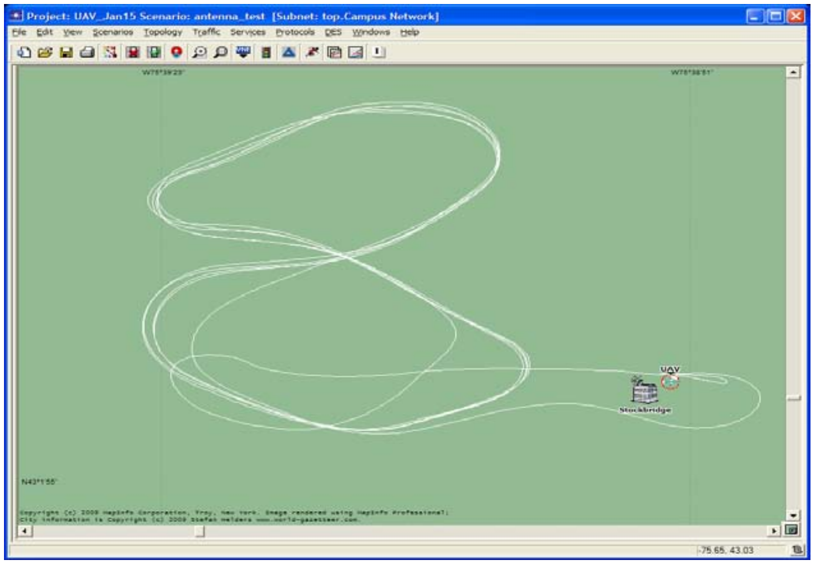


Figure 48: Flight Path Trajectory for Flight #2

D.2. Flight #3

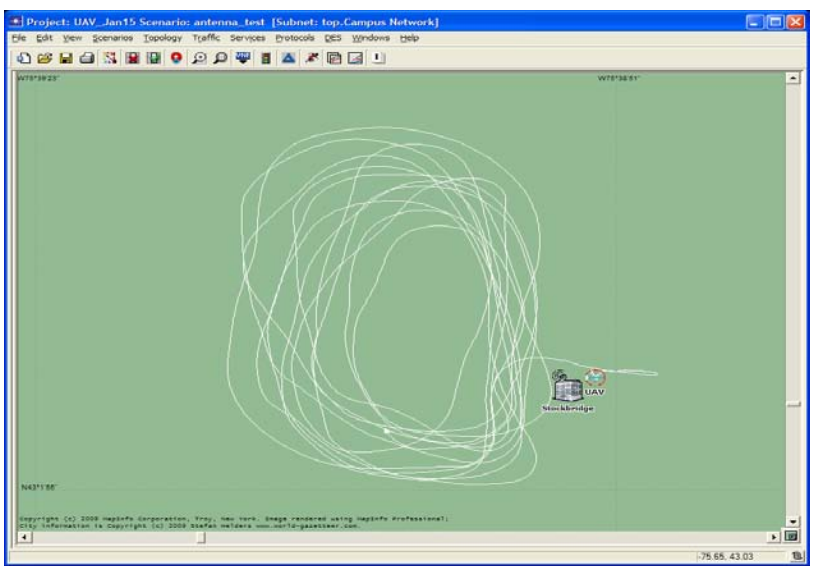


Figure 49: Flight Path Trajectory for Flight #3

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Vita

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14. ABSTRACT

Over the last few years, there has been an explosion in the use of Unmanned Aerial Vehicles (UAVs) in military operations, as well as civilian and commercial applications. UAV Mobile Ad Hoc Networks are fast becoming essential to conducting Network-Centric Warfare. As of October 2006, coalition UAVs, exclusive of hand-launched systems, had flown almost 400,000 flight hours in support of Operations Enduring Freedom and Iraqi Freedom. This document outlines our experience with implementing a statistically validated network model that emulates UAV network behavior during flight, using a leading simulation tool. Ultimately, there is a great need for a simulation environment that provides the capability to evaluate several aspects of networked UAVs, in lieu of large test-beds or costly flight testing. These simulations are designed to understand the characteristics and essential performance parameters of the delivered model. A statistical analysis is performed to explain results obtained, and identify potential performance irregularities. A systemic approach is taken during the preparation simulation phase to avoid producing misleading results.

15. SUBJECT TERMS

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