THE USE OF UNMANNED AERIAL VEHICLES IN PUBLIC SAFETY COMMUNICATION AND OPTIMIZATION OF COVERAGE
(CASE STUDY - COOK ISLANDS)

A THESIS SUBMITTED TO AUCKLAND UNIVERSITY OF TECHNOLOGY
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF COMPUTER AND INFORMATION SCIENCES

By

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April 2017

Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning.

Signature of candidate

Acknowledgements

This thesis was conducted as part of the requirement to complete a Master's Degree in Computer and Information Science at the Faculty of Design and Creative Technologies of Auckland University of Technology (AUT) in Auckland, New Zealand. During the period in which I conducted my research project, I received tremendous amount of help from various people and would like to acknowledge and thank those who have helped in many different ways.

Firstly, I would like to thank my supervisor Dr William Liu for the support and professional advice that he provided throughout the whole duration of this thesis. Without the weekly meetings, the constant emails, and your encouragement, this thesis could not reach its current form.

I would also like to thank all my other current study peers from the Master in Computer and Information Science who continues to share their ideas and offer support during my study periods.

Lastly, I would like to thank my greatest support in life and in my studies who are my lovely family, and especially my father Grover Harmon who continues to support and encourage me throughout the years living and studying in New Zealand.

Abstract

It is in the most critical situation when lives are at risk that the need for reliable and stable communication channels are essential. An effective communication infrastructure is extremely important for the following reasons: providing safety and emergency information to the general public, for first responders to coordinate rescue and recovery plans, families need to communicate to loved ones and check for their safety, and civilian needs to communicate with emergency first responders. The research conducted provides information on the latest advanced technology. Unmanned Aerial Vehicles (UAVs) such as drones are used as Unmanned Aerial Base Stations (UABSs) to provide temporary solutions to communication coverage in situations where part of an existing communication infrastructure is damaged and not functioning due to a natural disaster. By using the simulation, we are able to examine the throughput coverage achieved by utilizing the mobility feature of UAVs. The results of the simulation show that using UABSs in a dysfunctional communication system, can improve the throughput coverage and the spectral efficiency of the communication network when the UABSs are placed at optimized locations.

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Chapter 1

Introduction

1.1 Introduction

As technology advances, so does the increasing level of ingenuity among human-engineers who have contributed largely to the creation of the sophisticated and well-designed flying Unmanned Aerial Vehicles (UAVs). These UAVs are now used for basic to complex human activities, one of which is to provide a temporary solution to a damaged communication network. In this research, we looked at how UAVs are used to optimize coverage in the event of a natural disaster, focusing our case study around geographical information and related facts about the Cook Islands.

An UAV, also known as a drone, pilotless aircraft or robot plane are just some of the names given to this type of powered vehicle that does not require any onboard human pilot or crew. These UAVs can either be operated autonomously or remotely, can carry lethal or nonlethal payload and are either replaceable or recoverable [1]. The use of drones are wide spread and known for multiple purposes including personal, commercial, and military services. UAVs are also used for delivery, constructions, search and rescue, filming, surveillance, agriculture and gaming.

The use of drones for communication purposes is relatively new and with the right equipment and technology, it has been proven to provide critical communication services in remote and disaster-affected areas [2].

In the event when parts of a communication network architecture fail or are damaged, the use of unmanned aerial base stations (UABS) can play a huge role in public safety communication.

1.2 Background

In situations where lives are at risk, reliable and stable communication channels are essential to provide instant information in and out of a disaster area. An effective communication infrastructure is therefore extremely important for the following reasons; providing safety and emergency information to the general public; coordinating rescue and recovery plans to first responders; enabling familes to communicate with loved ones and checking their safety; and allowing civilians to communicate with emergency first responders [3].

Acknowledging the increase in occurrence of natural disasters, we need to ensure that the technology we use is effective and reliable. There is a wide range of computing tools and techniques used which are currently available to aid disaster and management response teams, including a range of platforms for aerial communication networks [4]. The critical aspect of such tools is their ability to collect and analyze information in a timely and reliable manner in the midst of a hostile environment.

The main problem discussed in this research is the issue of aerial communication coverage. While most UAVs are designed to provide communication access services from the sky, the location of the drone deployment will determine the effectiveness of coverage. By using a simulation matrix laboratory (MATLAB), we are able to apply certain scenarios and choose appropriate parameters to the system to produce results. The use of brute force search in this simulation provides the optimized locations possible for an Unmanned Aerial Base Station (UABS). Furthermore to the research, other issues and challenges to the process are discussed in the following chapters.

1.3 Problem Area

There is no doubt about the increase in occurrence of natural disasters around the world today. Earthquakes, tsunamis, cyclones, and floods among others are happening more often than ever, causing the destruction of infrastructure, vegetation and ultimately taking lives [5]. The severity and strength of these natural disasters are also increasingly making it difficult for humans to withstand their forces. In the event of a natural disaster, the most important matter that needs attention is to preserve human lives. The first 48-72 hours after a disaster hits is the most critical time, which means that the Search and Rescue (SAR) must be conducted immediately in an efficient and effective manner [6, 7].

The aftermath of any natural disaster is costly in terms of lives and resources, which is why it is important to consider and look into a disaster management system that utilizes modern technology such as UAVs for public safety communication as part of that disaster management system. The advanced sensing capabilities of the new generation of UAVs underpin the increasing success rates of rescue missions seen in recent emergency and response projects. These have been carried out in some parts of the world, including the 2010 Haiti earthquake [8].

Generally, in terms of wireless communication networks in many developed countries, internet connection is more affordable and accessible to many users due to the high quality networking infrastructure which is in place. These counrtries also use expensive quality technology resources and highly skilled technicians. However, the reality for some developing countries or even small island states, having such a complex network may be impossible, making the new technology of UAVs for public safety communication more challenging [9].

Acknowledging the need to find an effective and cost efficient solution to a disaster scenario, we focused our attention to ensure that communication channels are available in and out of the disaster-affected area. Study into modern technology and the newest advances in wireless sensor network and UAVs are increasingly viable due to their mobility, efficiency and cost effectiveness[10]. Given their complex design, UAVs require intense and in-depth study to really appreciate the full capacity of their potentials. However for this research, a simple but well equipped drone with adequate payload that can handle communication such as video, texting, and broadband is adequate. In other words, a drone equipped with transceivers that is a UABS or drone base station can help the demand of workload needed in a hostile environment [11].

Directly relating to our case study, the Cook Islands currently uses cellular base stations, available in various locations around the main island. These are the main physical and permanent tools used for cellular networks, however we know that such traditional technology has its limitations. A natural disaster will be a threat to cellular networks around the island and the Land Mobile Radio currently used on the island has its limitations, hence the need to find alternatives such as UAVs for mobile communication.

The operation of drones in the Cook Islands is relatively new, but they are mainly used for marketing and filming purposes. The Cook Islands is well known for its tourism reputation [12, 13] hence the use of drones for filming within this industry has increased substatially in the past five years. Introducing the usage of drones for disaster recovery requires more skills and high level of control, compared to the less intense purpose of just filming. It also requires specialized equipment. Currently such equipment is not available in the Cook Islands.

1.4 Motivation

There is no doubt this new generation will further advance the use of UAVs. For now, drones are potentially life saving tools used by those responsible for saving lives. More people are trying this technology and have documented their experience to let others know what UAVs are all about. This compilation of information provides support to new researchers. The process of researching takes time and money, but one thing is certain; information about technology is always advancing.

Operating a UAV, requires a fair amount of technological skills, time, and money. Drones are complex in nature but the size and mobility features make them ideal for aerial communication during critical situations. This makes it even more important to ensure that UABS are designed to cope with the level of demand by users of these services. So far, literature has shown a fair amount of research on ways to advance UAV designs and usability.

One area of great importance is the aerial communication coverage. This research presents specific methods used to better design the location or position of UAVs to optimize coverage when investigation is conducted using MATLAB. In stating the above, literature has shown other methods that do exist and are used to find the best locations for UAVs, to optimize coverage in a disaster recovery scenario, for example, the use of genetic algorithm (GA) [14].

The recent natural disaster of Cyclone Winston which affected the pacific island state of Fiji in March 21, 2016 is a good example for the rest of the Pacific Islands to look at. The severity of the cyclone which left 44 people dead, 32,000 homes damaged, and around 350,000 people affected has left people around the pacific, and others around the world to be more vigilant and take action to better safeguard their lives and property [15].

Today, technology provides various solutions to people's adversities. The use of drones or UAVs in assisting rescue services during a natural disaster is well documented and discussed in many research papers, and this research may add more to the existing literature.

1.5 Focus and Objectives

This study focuses on the use of drones equipped with mobile communication capabilities, that can be deployed during times of natural disasters to create a new medium of aerial communication network. During a natural disaster, it is likely that some or all parts of existing communication base stations will be destroyed, and communication is a critical factor and a priority structure in the aftermath of a disaster.

The objectives of this research is to conduct a simulation, testing various locations of UAVs within a given area of disaster scenarios, to recreate a connectivity point and optimize coverage.

The idea of deploying an UABSs within the area of our case study will be challenging, as it is relatively new. The desired outcome of this study is to explore a lower cost option for disaster communication by using UAVS to create large area coverage for communication access and ultimately save more lives and properties.

1.6 Structure of Thesis

This thesis is divided into five parts as shown in figure 1.1 . Chapter 1 is the introduction, and it presents information about the background of the research, states the importance of the topic and the reasons for doing this research. The next section in the chapter describes the problems in the field of study followed by the motivation for doing this research. The objectives and focus of the research are further discussed in subsequent sections.

Chapter 2 is the literature review, which is a collection of information supporting the topic. The literature review focuses on the use of drones for communication purposes in the event of a natural disaster. There is information on the different types of UAVs, how they work and are designed. Other articles provide similar informations detailing the benefits, and costs related to UAVs, which are also stated in this section. Furthermore, a detailed information on the history of drones, the different characteristics of drones, how drones are used, what drones are used for, who uses the technology, and why the technology is so popular in many areas, including search and rescue, filming, delivery and other areas.

Chapter 3 defines the methodology and research design. The first part looks at other research methods used by other researchers to determine the best possible location of an Unmanned Aerial Vehicle such as drones to maximize coverage. Based on the review, a method in which a simulation is conducted as part of various researches is also used in this research, and the results are analyzed and used to answer the research questions and other secondary questions. The next section of this chapter describes the research design. In this section, the research problem is further discussed followed by the primary research question and sub-questions. The last part of the research design is the research plan, where each of the steps taken to complete this thesis is described. Another area described in this chapter is the data requirements and analysis section, where the four phases of the research is further discussed including data creation, processing, collection, and data analysis. The final section of the chapter describes some of the limitations to the research methodology.

Chapter 4 is the simulation studies, looking at figures and tables and the results, and how they all come together. This continues from chapter 3 where the simulation is carried out and the results of the simulation are stated in this chapter. The results are clearly explained and research questions are answered. Furthermore there is an in-depth discussion around two different scenarios used in MATLAB. The different scenarios are determined by the set of different system parameters in the simulation. Conducting the simulation allows the use of brute force to provide the optimized locations possible for an UABS that can improve the level of aerial communication coverage.

Chapter 5 is the summary of all findings, recommendations and conclusion. It also provides details about possible future works.

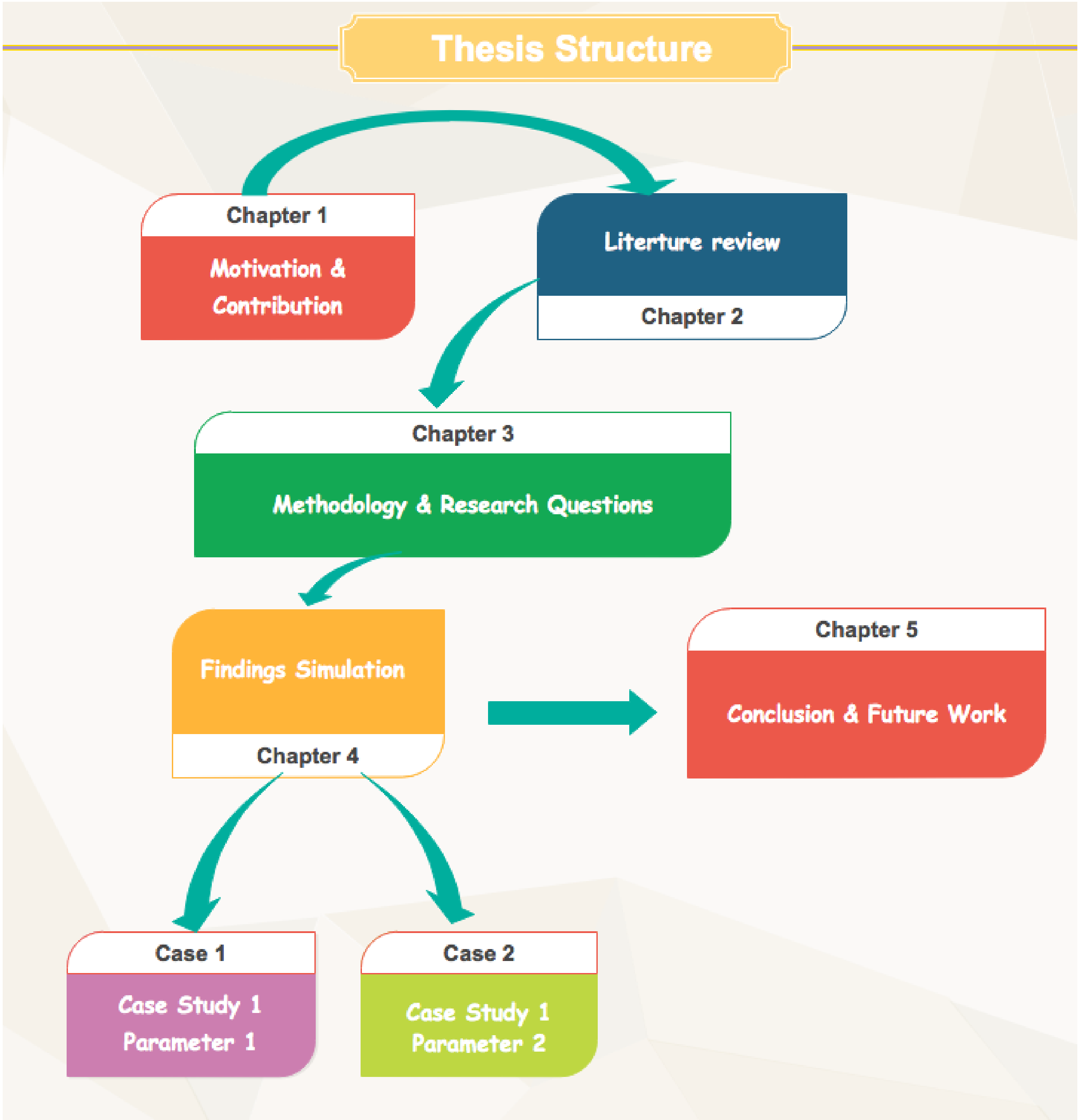

Figure 1.1: Thesis structure

Chapter 2

Literature Review

2.1 Introduction

In recent years technology has become the driving factor behind major operations in different markets around the world. The communication networks especially rely heavily on technology to function, especially the infrastructure of the internet. The issue is that only some parts of the world will have this infrastructure in place. A localized service infrastructure is critical to access the communication globally. Since not one size and type of communication network service can fit the needs of every community, it's worthy to explore all possibilities.

Most communication technologies rely heavily on a localized backbone network to function, so when the network fails, it causes difficulties to any communication channels, including public-safety and emergency communications. Recently, the relatively new and fascinating idea of having UAVs as aerial base stations has gained attention in public safety communication. UAVs such as quadcopters and gliders can be operated as UABS, that can be deployed rapidly and form part of a heterogeneous network (HetNet) architecture as discussed in [16].

UAVs are considered critical in forming the advanced system of communication, which is originally created for military purposes and used in situations that are considered dangerous and risky for man. For public safety communication (PSC), UAVs are now considered the possible solution for various reasons. For real time on demand services, the Long Term Evolution (LTE) 4G and the upcoming 5G [17] can offer higher data rates [18], which is better during a natural disaster, compared to the Land Mobile Radio (LMR) alone that can only provide voice and lacks capacity, interoperability and functionality [19]. The broadband aerial capability of most UAVs can assist first responders, who must also be equipped with the technology that provide broadband data to increase coverage and interoperability [20].

This chapter discusses an overview of literature on the relatively new UAVs and how these are used within a typical networking infrastructure. These UAVs can be operated as UABSs that can be deployed rapidly to form part of the heterogeneous network (HetNet) in a hostile environment such as that during the aftermath of a natural disaster. The chapter begins with the general overview on UAVs including it's definition, history, classification, performance characteristics and it's different applications. Furthermore, and importantly, there is a description of the Heterogeneous Network (HetNet) where the traditional networking system is compared to the alternative and advanced wireless communication system. Finally, more information is presented on the rules and regulations surrounding the use of UAVs as well as it's common advantages and disadvantages.

2.2 General overview about UAVs

2.2.1 Definition of UAVs

The term Unmanned Aerial Vehicles (UAVs) is commonly used in the field of Computer Science, Robotics and Artificial Intelligence and Remote Sensing Communities. At times UAVs are mentioned in the literature as Remotely Piloted Vehicles, Remotely Operated Aircrafts (ROA), Remotely Piloted Aircrafts or Unmanned Vehicle Systems (UVS) [21] or flightless pilots [22]. UAVs are often the eyes in the sky providing critical information that man would not otherwise be able to get.

2.2.2 History of UAVs

It was an exciting period in history when UAVs took over some of the most critical and dangerous missions of men. Literature has provided details about the evolution of UAVs way back to the late 1800's when balloons were first used. While the origin of UAVs is not clear, literature has pointed to America as the leading founder of the technology [23] and [24].

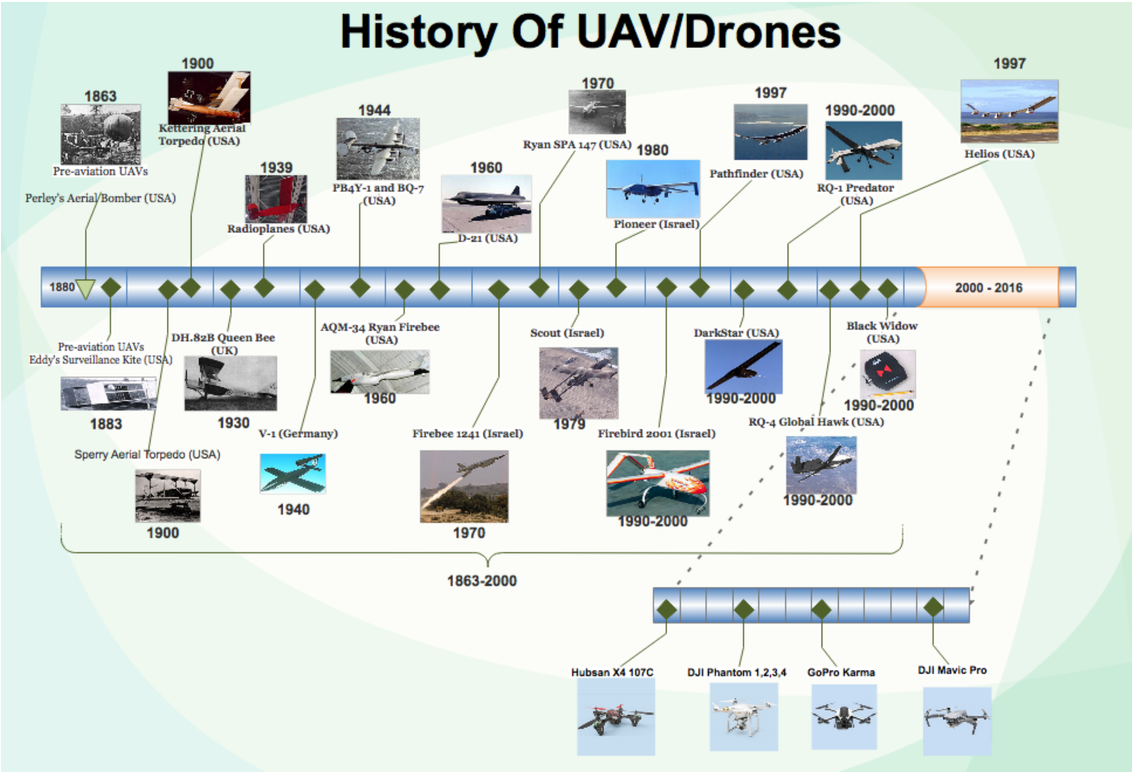

Figure 2.1: The History of UAVs time line

2.3 Classifications of UAVs

UAVs can be classified in at least two different ways. One is according to their performance specification and the other is based on their mission [25]. Generally, UAVs have the following specifications: weight, endurance, range, payload, speed, cost, wind loading, engine type and power. In terms of mission, the most common include surveillance, combat, resupply and aerial delivery. This research focuses on the aerial communication mission of UAVs. Flight time, payload, power and cost are performance specifications which are critical for aerial delivery missions.

2.3.1 Flight time

The length of time any UAV can fly depends on the nature of its design. All UAVs are uniquely designed and have different characteristics.For aerial delivery low-altitude platforms are used and, depending on the capacity of the battery, the payload of the drone and its mobility pattern, these drones can fly 10 to 40 minutes [26].

2.3.2 Payload

In terms of payload, the weight a drone can carry varies depending on the size of the drone. Generally, larger drones can carry between 5-7kgs and smaller drones may only carry a few grams [27].

2.3.3 Power

There are two possible scenarios to consider in regards to the power capacity for UAVs [28]. In the first scenario, the power for the UAVs and it's load comes from the same source. When the UAV is carrying communication network equipment, using the same power source the flying time can be limited and substantially affecting the life of the network. An important point to note here is that whether a UAV is in a state of transmission, reception, idle, or sleep mode, energy consumption is still active. The overall design of the network determines power or energy level to run a UAV network. In the second scenario when separate power source is used for different parts of the UAVs, the flying time is relatively higher compared to the first design as mentioned in scenario 1. The only concern with this design is that weight will be the issue.

2.3.4 Cost

The cost of a drone varies depending on the size and complexity of it's construction. What really determines the price of a drone lies in their ability to do things that other technologies may not be able to perform. This means that the more complex and critical task a drone can perform, the likelihood that its price is at the highest range. The cost of a top of the line drone used for military purposes can reach in the millions. On the other hand some drone prices are relatively inexpensive, costing as little as a few hundred dollars. These are the very basic drones used by many people today for fun and hobbies. Generally, UAVs have to be lightweight, robust in nature and economically affordable in order for this technology to be attractive [29].

The following table provides more details about the different types of UAVs and their respective characteristics.

Table 2.1: UAVs and their characteristics

Name	**Payload**	**Control Range**	**Flight time (With Payload)**	**Price**
DJI Matrice 100	3.6 kg	5 km	40 Minutes	$3,299.00
FreeFly ALTA 8	18 kg	2 km	10 Minutes	$17,495.00
AZ 4K UHD	20 kg	N/A	20 Minutes	$8,999.00
DJI Matrice 600	8 kg	5 km	15 Minutes	$5,000.00
DJI S900	8.2 kg	N/A	18 Minutes	$1,199.00

2.4 Applications of UAVs

Today we continue to see an increase in interest over the use of drones, due to their flexibility, versatility, easy installation, and relatively low operating cost [30]. The following applications are just some of the promising new ways drones are being used.

2.4.1 Search and Rescue

To conduct a search and rescue mission involves four steps [5, 31]. The first step involves determining the search area, followed by setting up a command post in the most appropriate location of the search area. Next the first responders and volunteers are divided into smaller units of scouts and rescuers. The final step involves the command post retrieving vital information from the scouts and passing this onto the rescuers so they know exactly where to focus their rescue effort [32]. UAVs can be used for search and rescue projects by providing surveilance in areas with difficult terrain [33].

2.4.2 Delivery

Drones are now being used to deliver items including goods for consumption, fast food delivery, grocery, medicines, and other materials [34]. A reasonable limit payload for drones that are now being used for delivery is about 2.5kg, which is also about the same weight as 83% of packages delived by Amazon [35]. Fedex also has an average delivery package weight of less than 5kg. No doubt this model of technology can allow more and more weight in package delivery in the coming years. While this model of delivery by drones is still at infancy stage, large businesses in the market have already started with a drone package delivery prototype including Amazon, DHL, Matternet and Google. This technology provides on-demand delivery and is cost competitive compared to any other ground-based network [36, 37, 38, 39, 40, 41, 42].

2.4.3 Filming

Drones are now popular within the filming industry for similar reasons to why it is used for search and rescue or other services [43]. The use of mobile camera drones provide a whole new experience to filming as opposed to the fixed and static camera that cannot produce the same level of accuracy and entertainment. For example, when filming sports events, a mobile camera drone is able to fly over specific areas of the field to film the sport in action providing maximum satisfaction to viewers who watch the game on TV [44].

2.4.4 Agriculture

The use of drones for farming and agriculture is a smart move [45]. UAVs are being used for inspecting the current health state of farming and providing solutions to various stages of farming such as plowing and harvesting. The use of UAVs allow farmers and agricultural personnel to have a bird's eye view of their field that enables them to make effective evaluation and take action [46]. For example, when a drone is equipped with a computer vision technique, its possible to differentiate between a tilled soil and soil that is untilled [47]. It also allows it to measure the required water level of a given area. This also indicates whether a plot of plants may or may not need more water. Ultimately in using this technology, farmers are able to make better use of their time on other areas of farming while drones conduct surveying of the field and providing vital information back to farmers. Furthermore image surveying techniques are made possible by deploying quad-rotors with a coverage trajectory planning capability to enhance precision agriculture [48].

2.4.5 Military

The use of UAVs by the military is highly documented and many authors have indicated that most UAVs were even created for the purpose of aiding military works [49]. The military's primary purposes for UAVs are for border surveillance, reconnaissance and strike missions [50]. The military has been using this form of aerial services for the past 25 years and still currently operating many military missions with the service. The huge advantage for the military is the many lives spared from avoiding man-to-man combat that are now being carried out by UAVs. The level of technology has also changed dramatically in the way the military has designed most UAVs, providing more precision and speed capability compared to twenty years ago.

2.4.6 Surveillance

Surveillance is a general term used in many cases, such as border surveillance, marine surveillance or traffic surveillance. UAVs provide the best options when it comes to information gathering [51]. A single UAV equipped with proper technology such as a mobile camera, thermal camera and motion detectors is able to capture accurate and raw data. This data can be used by a command center who then takes appropriate action [52].

2.4.7 Infrastructure reconnaissance

Examining the structural damage to a building caused by a military strike or natural disaster is a dangerous and time consuming task, but with drones equipped with cameras and other communication devices, engineers will get accurate and raw information they need within a short period of time and take appropriate actions [53]. An unmanned aerial vehicle can maneuver around unpredictable small and dangerous spaces for humans. People on the ground are able to assess the level of damage to infrastructure.

2.4.8 Gaming and recreation

Because the cost of an entry level drone is affordable to many people, they are now commonly purchased for recreational purposes. Clubs often organize gaming events that may include races or obsticle courses. In the gaming world, drones are being used in simulations such as Play Station games, to depict what a drone can actually do in a real war zone. Military personnel also use gaming simulations for training purposes, and these have been shown to increase the skills and level of confidence of sodiers [54].

2.4.9 Journalism

News organizations and journalists in general are using drones to develop daily and breaking news coverage, conduct investigation on certain stories, reporting on disaster and conflict situations, and conducting other general photojournalism [55].

2.5 Heterogeneous network (HetNet)

A Heterogeneous Network (HetNet) is a promising new networking topology that looks at improving the efficiency spectral per unit area of the network. It is a combination of macro plus micro base stations including pico, femto and relay base stations. In the heterogeneous network, deployments of base stations are flexible and relatively cost efficient allowing all users to experience a uniform broadband coverage. Mobile communication operators continue to expand and widen the spectrum of their current traditional networking system because of the increasing demand of mobile communication services [56].

The following table describes the different characteristics between the traditional networking system and the alternative Advanced Networking system.

Table 2.2: Characteristics between the traditional networking system and the alternative Advanced Networking system

Traditional Networking System	***Advanced Networking system***
Homogeneous networking system – consists of similar macro base stations.	Heterogeneous networking system – consists of various macro and micro base stations.
Narrow band communication technology.	Wider and improved spectral efficiency and bandwidth.
It uses Land Mobile Radio (LMR) that only provides voice communication technology [57]	It operates the latest Long-Term Evolution (LTE) wireless broadband technology [57]
Capacity limited platform	High Speed communication infrastructure.
Requires fair amount of human intervention	Its highly operated autonomously
Its a well-planned process and layout	Network is flexible
Complex and costly	Less complex and low cost
High powered base stations	Low powered base stations
Highly static	Highly dynamic
Macro Base stations	Utilizing low-altitude UAVs

2.6 UAV Network Topology

According to the authors of [50], what makes the UAV network topology systems different from other wireless networks is that it is highly mobile and dynamic. The links in this network is established intermittently and the topology is fluid with the number of nodes that alter frequently and links changing. The frequent changes in the UAV topology is due to the following reasons: the relative changes in the position of the UAV, when a UAV needs to be brought down to the ground for recharging, when a UAV is out of the network due to malfunction. The changing position of the nodes also affect the links performance, whether it be in connection or disappears at any given time.

The dynamicity of nodes is likely to force a UAV network to organize and re-organize frequently. Meaning that the network should have self-organizing capabilities, considering tolerant delay capabilities, a flexible and automated control system, a seamless handover and employs an energy saving mechanism.

2.7 Multi-UAV network topology

Common topologies in a multi-UAV network includes, a star, multi-star, mesh and hierarchical mesh topologies [50].

2.7.1 Star

In a star topology, all UAVs are connected directly to one or more nodes on the ground. All communication among UAVs are routed through the ground nodes as described in figure 2.2 (a) below. Furthermore, in a star topology design, it requires more expensive high bandwidth downlinks. It is also likely to experience higher latency and more blockage of links. As the nodes are highly dynamic, the steerable antennas may be required to face towards the nodes on the ground at all times.

In terms of the multi-star topology as shown in figure 2.2 (b), you will notice , that it is quite similar to the star topology, except the UAVs would use multiple stars and one node from each group of UAVs to connect to the station on the ground. A common downside for both star topology, is the high rate of latency as the downlink signal is longer than the inter-UAV distance. All communication must go through the control center on the ground. If this ground center fails, the inter-UAV communication will also fail.

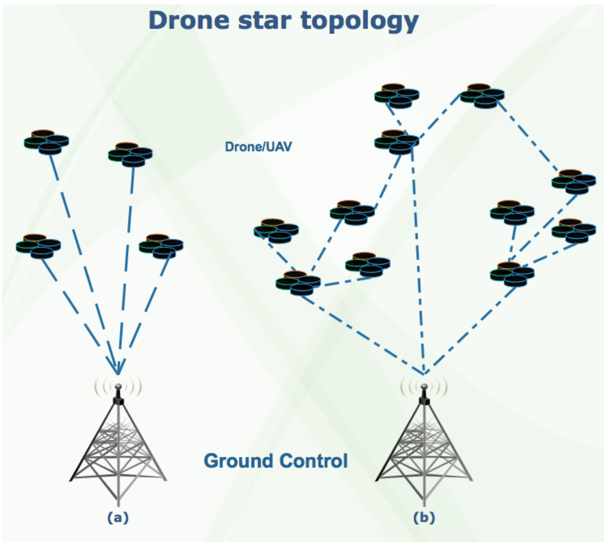

Figure 2.2: a) Star configuration network. b) Multi-star configuration network

2.7.2 Mesh

The mesh network is more flexible and reliable, it offers improved and better characteristics performances [58]. The nodes in the wireless mesh network are interconnected and can communicate directly on more than one link [59, 60]. Furthermore, a message or communication in general can pass through these intermediate nodes and in multiple hops, these packets will find its way from any source to any destination. The mesh network can use either routing or flooding techniques to send packages. Most importantly, the routing technique is able to deliver messages in various forms and can be used during emergency situations, where data is routed from the command and control center, directly to emergency responders or people and vice-versa.

The figure 2.3 (a) and (b) below shows flat and hierarchical mesh networks.

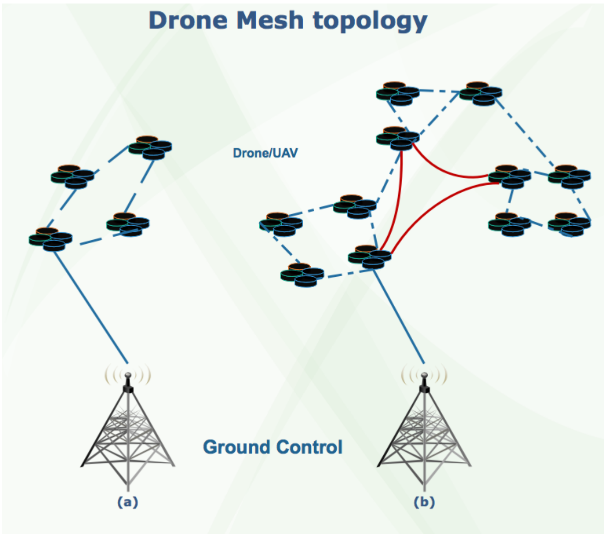

Figure 2.3: a) Flat mesh network. b) Hierachical mesh network

2.8 Multi-UAV systems vs Single UAV system

A single UAV system consists of just one aerial node created by one large UAV, and one or more ground nodes. In contrast, a multi UAV system consisting multiple aerial nodes and the UAVs are smaller in size and are less expensive and they all work in a coordinated manner. The key advantage of a multi-UAV system over the Single UAV system is that the former is more reliable and survives through redundancy. While the later will cause the network to reorganize and maintain communication through other means or nodes, if the single UAV in the system fails.

The following table below provides more details on the different UAV systems.

Table 2.3: Evaluation between a Multi and Single UAV System

Feature	Multi-UAV System	Single UAV System
Failure rate	Low failure rate and can reconfigure its system	High failure rate, Mission fails
Scalability	Medium to high	Limited
Survivability	High	Low or Poor
Mission Speed	High or Fast	Slow
Required Bandwidth	Medium	Very High
Type of Antenna	Directional	Omni-directional
Level of Control	High	Low to Medium
Failure to coordinate	Present	Low

2.9 Handover

Handover is a process that allows for a total continuity of communication within a network with minimum latency rate during the handover process [61], [62]. In a highly dynamic networking system such as that of a Multi-UAV topology system, there are many reasons that may require the process of handover to take place.

Reasons:

1. The relative changes in position of the UAV.

2. When a UAV needs to be brought down to the ground for recharging.

3. When a UAV is out of the network due to malfunction.

In all these cases, the network needs to reconfigure and the continuous video, voice and data sessions are needed to be handed over to another functioning and available UAV within the network.

There are two types of handover or handoffs in UAV networks, which are hard and soft handovers, that can also be classified as horizontal and vertical handovers.

2.9.1 Hard Handover

In the case of a hard handover, the end user will experience a disruption or loss of connection during the handover process. The connection from the serving cell tower is broken and then reconnected to another available cell tower.

2.9.2 Soft Handover

In a soft handover, there is no disruption in the communication by the end user. The connection is well established with the new available cell tower before it is broken from the existing serving cell tower.

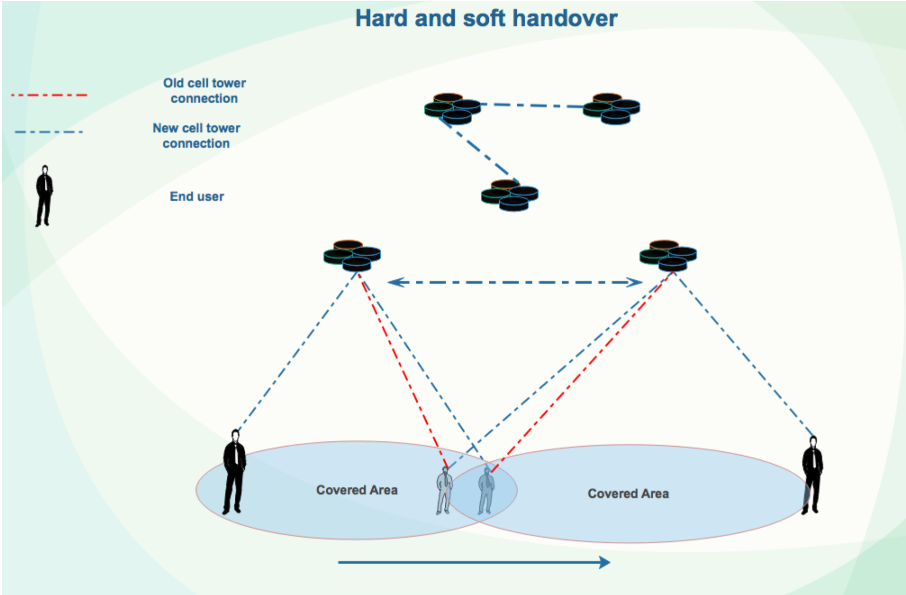

Figure 2.4: Soft and Hard handover

2.9.3 Horizontal Handover

In a horizontal handover, there are multiple access points within the same network, which allows the user to move freely and still stay connected.

2.9.4 Vertical Handover

In a vertical handover, the connection is transferred between two different types of devices or technologies such as that of a cell tower to a UABS.

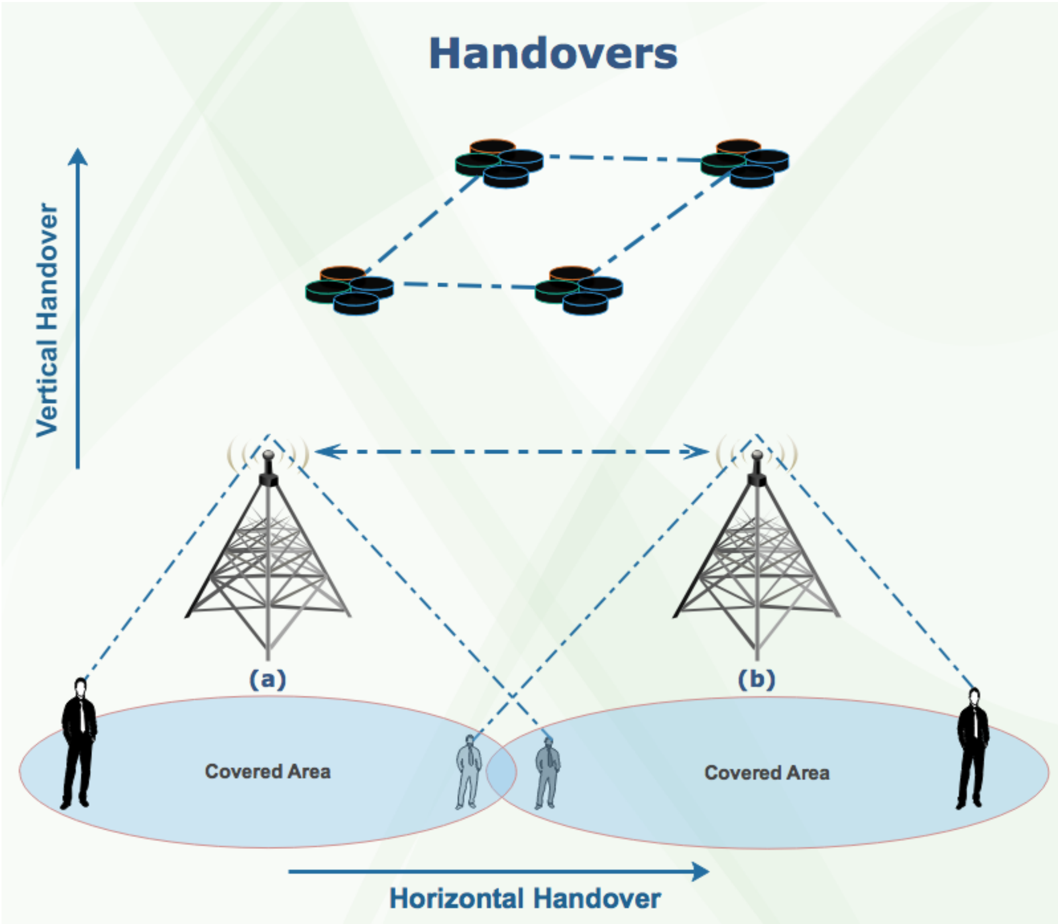

Figure 2.5: Vertical and Horizontal Handover

2.10 Cellular network

Cell towers are the main tools used for wireless communication which enables voice and data services to many internet users via their mobile devices and smart computers. The availability of cell towers enables connections to a vast area beyond just our homes. How cell towers works are further discussed below.

Figure 2.6: One of the cell towers on Rarotonga

2.11 Coverage

Compared to the traditional base station, combination of mix base stations can cover more areas due largely to how it is positioned. Having a UAV flying in the air at different heights, provides an angle-looking path for signals that covers a larger area of the ground from the sky [27].

The figure below provide a modest demonstration of area coverage based on heights and the number of UAVs deployed. You can see in figure 2.7, the higher the UAV is placed, the larger the area of coverage will be.

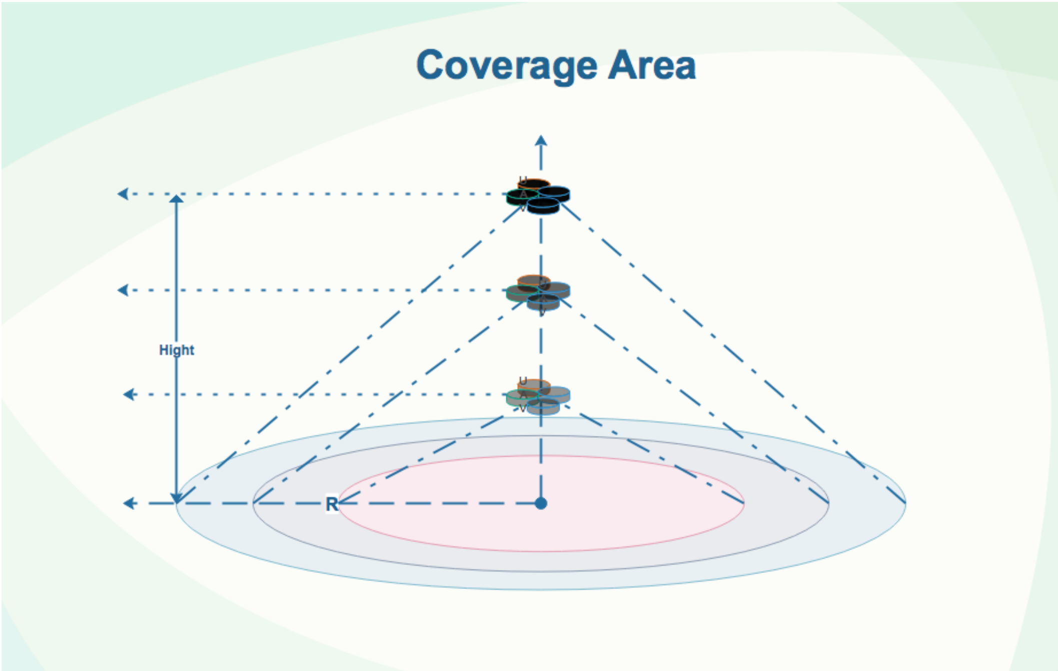

Figure 2.7: The coverage area of base station based on height of UAVs

Figure 2.8 below, shows the area of coverage based on multiple UAVs deployed, which provides an even larger area coverage compared to a single UAV deployed.

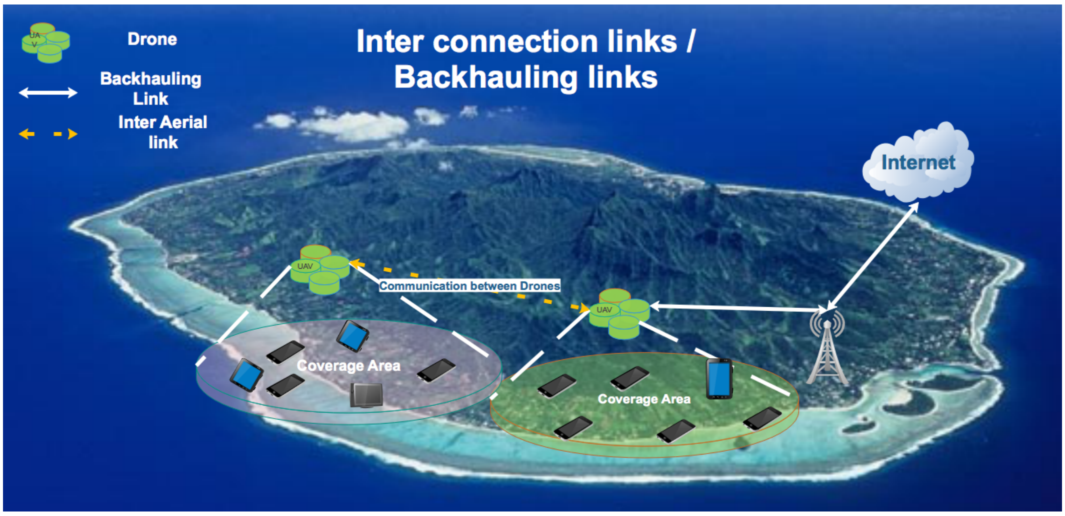

Figure 2.8: Multiple UAVs deployed

Using multiple UAVs provide various advantages in terms of area of coverage as opposed to a single UAV case. The main advantage of a multiple UAVs scenario is that it provides redundancy where in such cases one UAV fails, another can take up the load and connectivity is maintained to some extent. In terms of coverage, by having multiple UAVs, it helps increase the maximum size of the area of concern. Having a single UAV, minimizes the area of coverage in a designated area of concern [63].

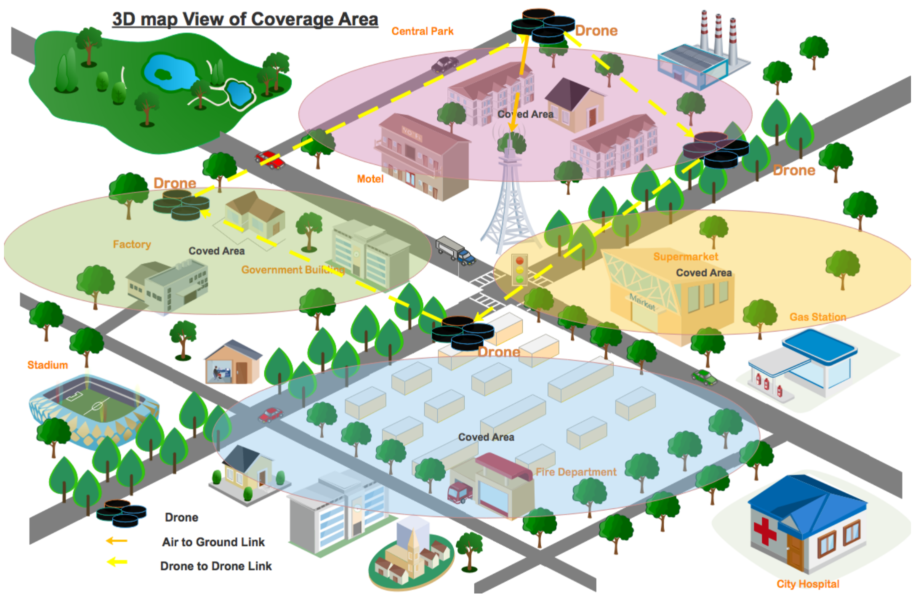

Figure 2.9: Multiple UABs deployed in 3D coverage

The figure 2.9 above shows the effect of having multiple UABSs and the coverage range in 3D.

2.12 Advantages and disadvantages of UAVs

One major barrier to the operation of drones is having a safe and regulated environment to which this technology is controlled. Generally, in many countries, to operate an aerial network requires stringent regulatory and legislative controls. Hence why it is very important to be aware of these rules and regulations while operating any UAV.

The big question that may come with the operation of drones is the safety and privacy measure of such technology. Recently media has shown an increased interest of people operating drones for many purposes. However some of these activities may have fallen onto the negative side of the law. The advantages and disadvantages in operating UAVs are stated below [64].

2.12.1 Advantages

1. Deployment of UAVs – The designs of many drones make their deployment easy as they do not require any runway for takeoff or landing.

2. Affordable – Drones are much cheaper compared to other flying airplanes or airships, making it an easier choice for lower income users.

3. Flexibility – Drones are designed for easy movement allowing the technology to reach dangerous and high risk areas.

4. High level of safety – Drones exist to provide safety to human lives. It requires no onboard pilot or crew, making it safer in the event a drone fails or is destroyed.

5. Operated autonomously – UAVs are equipped with technology that allow them to be operated alone without constant human monitoring.

6. No fix hour of operation – with drones, the flying or operation time depends on the user. Day or night time, the drone can fly.

7. Accuracy – Drones are always accurate unless there are technical issues to the machine. Drones are programmed to do exactly what it is meant to do.

2.12.2 Disadvantages

1. Invasion of privacy – the common issue faced by users of drones is privacy. While drones are capable of providing information from the air using aerial networks, others are using this technology to excessively invade the privacy of others.

2. Abilities are limited – On the downside of this technology, drones have limited payloads and limited flight time due to their rather small size.

In terms of this research, the biggest challenge relating to a low-altitude UAV, is the ability to determine the optimal location to maximize coverage where the communication network will benefit the most [65]. In a hostile environment, the most challenging task when using a drone to provide communication is the ability to position a UABS in a location that can provide optimum coverage. In terms of more open issues and challenges relating to some aspects of UAVs applications, refer to [66].

2.13 Other related works

In this portion of the chapter we look at how other researchers conduct their research similar to the topic of Unmanned Aerial Vehicles (UAVs) and how they can be used in many different situations. In particular, we consider the way in which different types of UAVs are controlled and designed to provide communication and a range of aerial coverage.

2.13.1 Quadcopters

First we look at a drone designed to be as lightweight and low cost as possible. According to [29], it looks at building a quadcopter, which is simply a powered drone that can also provide and act as a micro cloud server. The quadcopter is built with a single board computer Raspberry PIs and a lightweight virtual Operating System (OS) called Dockers and these are then integrated with a lightweight drone.

This quadcopter is then controlled by a laptop manually from on the ground, which is connected through WI-FI via a portable WI-FI access point provided by the PI as discussed also in [67]. This control process also makes use of a gaming joystick which basically controls the drone manually. In order for this manual process to work, a python module called Pygame is used. This enables the joystick to imitate a RC transmitter with different buttons and 2-axis joysticks used as controls for various movements of the drone, such as pitch, roll, yaw and throttle. In order to monitor the drones progress, including the altitude, orientation, the battery level, also the GPS coordinates, a graphical user interface is created. Another software called Robot Operating System (ROS) is used to connect the PI and the base laptop. The program will send and receive data in a simplified manner with the concepts of reproducing and subscribing data.

Looking at the challenges involved with quadcopters, we discovered that these types of drones have very little battery life, due to the way their batteries are designed, which ultimately reduces flight time. Alternative sources of power energy such as hydrogen can increase the duration of flight time to about two hours.

The figure below shows interesting features of a quadrotor, another form of UAV that is highly customizable and price effective, well suited for high-level UAV control tasks. For more details on the design refer to [68].

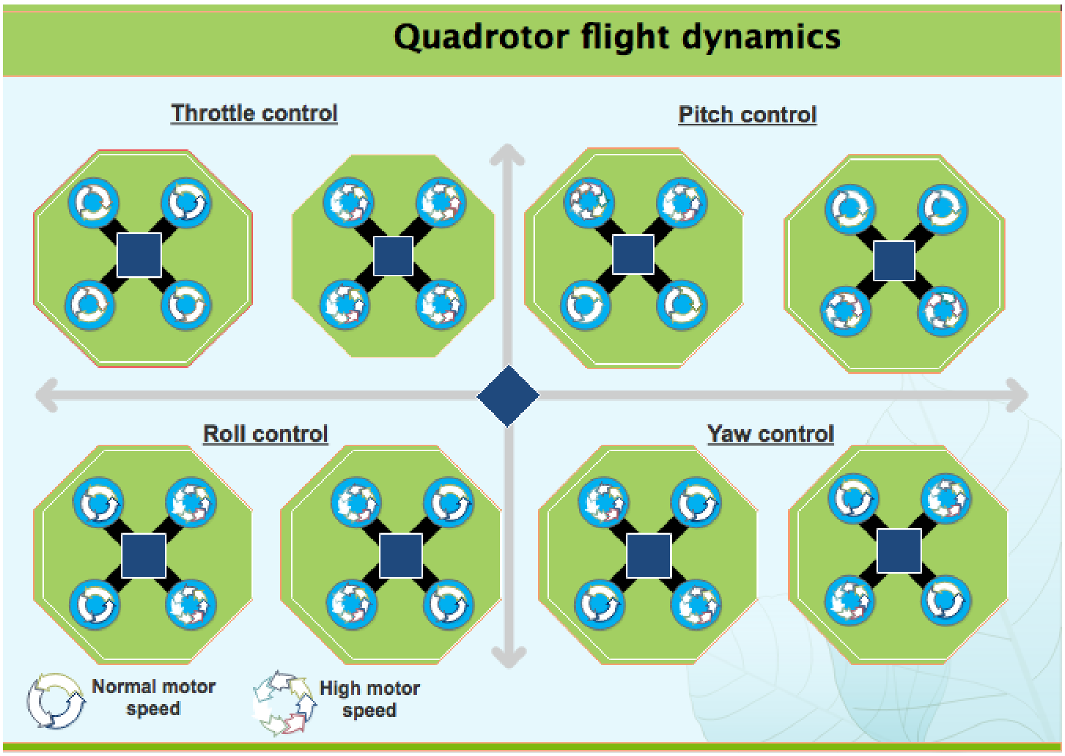

Figure 2.10: Quadrotor flight dynamics

2.13.2 Helikites

Another form of Unmanned Aerial Vehicle (UAV) used to provide connectivity or communication from the sky is a Helikite. Chandrasekharan et al provide insight into the world of Helikites. The helikite is designed to have both characteristics of a helium balloon and a kite that forms a single tethered aircraft.

The features of a helikite that attracts users include its relatively high altitude. It uses a combination of helium and wind to lift and reach its target altitude. A helikite has the ability to carry more payloads compared to other aerostat in any type of wind condition. Another feature of a helikite is that it requires no electrical power but is operated through the release of helium gas in its tight gas inner balloon, making it relatively inexpensive compared to other aerial platforms. Lastly helikites require fewer rules and regulations surrounding their operation, compared to other UAVs like drones.

The helikite is designed in a way which allows it to carry a battery, an antenna, and Remote Radio Head (RRH). The helikite is then anchored to the ground with a fiber optic cable that connects it to an operating station available on the ground.

The limitation relating to the helikite, is that the software and hardware produced by telecommunication companies are not designed for this type of platform [69].

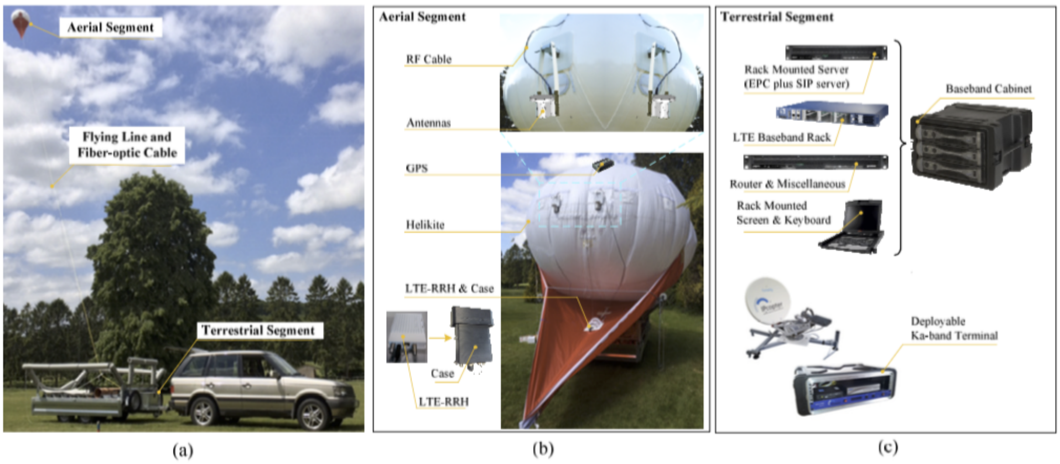

Figure 2.11: Design of the Helikite technology [69]

2.13.3 Google's Loon project

The study into the Google's Loon Project was initiated to accommodate the need for internet connectivity [70, 71] . According to another research conducted by Google, around 4.5 billion people are still out of reach and have no access to internet even with the level of modern technology offered today [72].

The project Loon involves deployments of many balloon at high altitudes about 60,000 feet into the earth's atmosphere. This balloon can stay up in the air for a period of over three months about 100 days. It also travels at twice the height of a commercial plane that is 20 kilometers above the earth [73]. Unlike fixed cell towers on the ground where the end user is dynamic and the cell tower is static, loon balloon operates vice versa, where in this case the balloon is dynamic and moves with the wind direction, while the end user is stationary and connects to the closest loon balloon Access Point (AP). The balloon can cover an area of around 40km in diameter, which allows people within the covered area to connect to the balloon using antenna fixed on their buildings. The balloon can provide internet connection with speeds similar to 3G (10Mbps) and using 2.4 and 5.8 GHz from the ISM band.

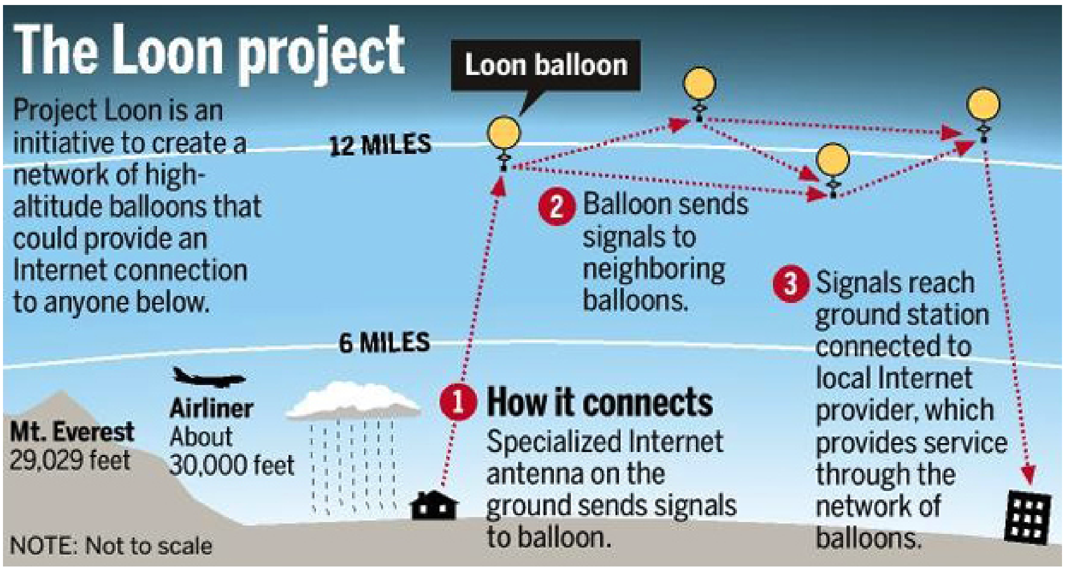

Figure 2.12: Google "project Loon" [72]

The general common barrier to internet access is infrastructure and affordability. According to this research, the challenges faced by the project relates directly to the nature of the technology, which is its balloon-based system. As the balloon uses helium gas, some critics have stated that a helium balloon is unable to stay afloat for more than 3 days, however Google who managed to keep the Loon Balloon up for about 100 days, proved this wrong.

Secondly, other critics have concerns about the level of helium supply in the future. It has been predicted that there will be shortages on the supply of helium, as well as prices for this commodity will increase. Google has a solution for this, to use alternative sources including the use of hydrogen fuel balloon. Another specific problem related to balloons is the critical process of controlling or steering the balloon while in the stratosphere [74]. At present, Google depends on the wind directions that exist in this layer, and while at some locations the wind may provide favorable conditions to the steering process. This is not always the case, and at the worse end, the balloon will either end up at the North or South Pole.

Table 2.4: Project Loon

Google Balloon (Loon)	
Equipment	Project Loon air-balloons is equipped with solar panels.
Control	Balloons will basically be floating on atmospheric winds so it will not have controlled precision of winged aircraft.
Flying hight	Floating 60000ft (10km) above the,ground
Flight time	Loon balloons are being designed to stay aloft for 100 days in air
Signal	Uses Radio signals to link balloons to volleyball sized antennas mounted on tops of homes & businesses
Landing	Project Loon has a parachute for landing to safety in case of emergency equipment failure.
Placement	Balloons are placed evenly apart to cover a large area

2.13.4 Project Aquila

Project Aquila is a study conducted by Facebook on a technology that aims to connect people in remote parts of the world to a mobile broadband network. Also acknowledged in this research is the 1.6 billion people living in areas without broadband connection creating an opportunity target demand on the new technology which Facebook calls, Project Aquila. It is simply a creation of a fleet of solar powered aircrafts, capable of flying at high altitude and providing a broadband coverage to the ground area at a range of 60 miles wide. These planes can stay airborne for a period of 90 days at a time.

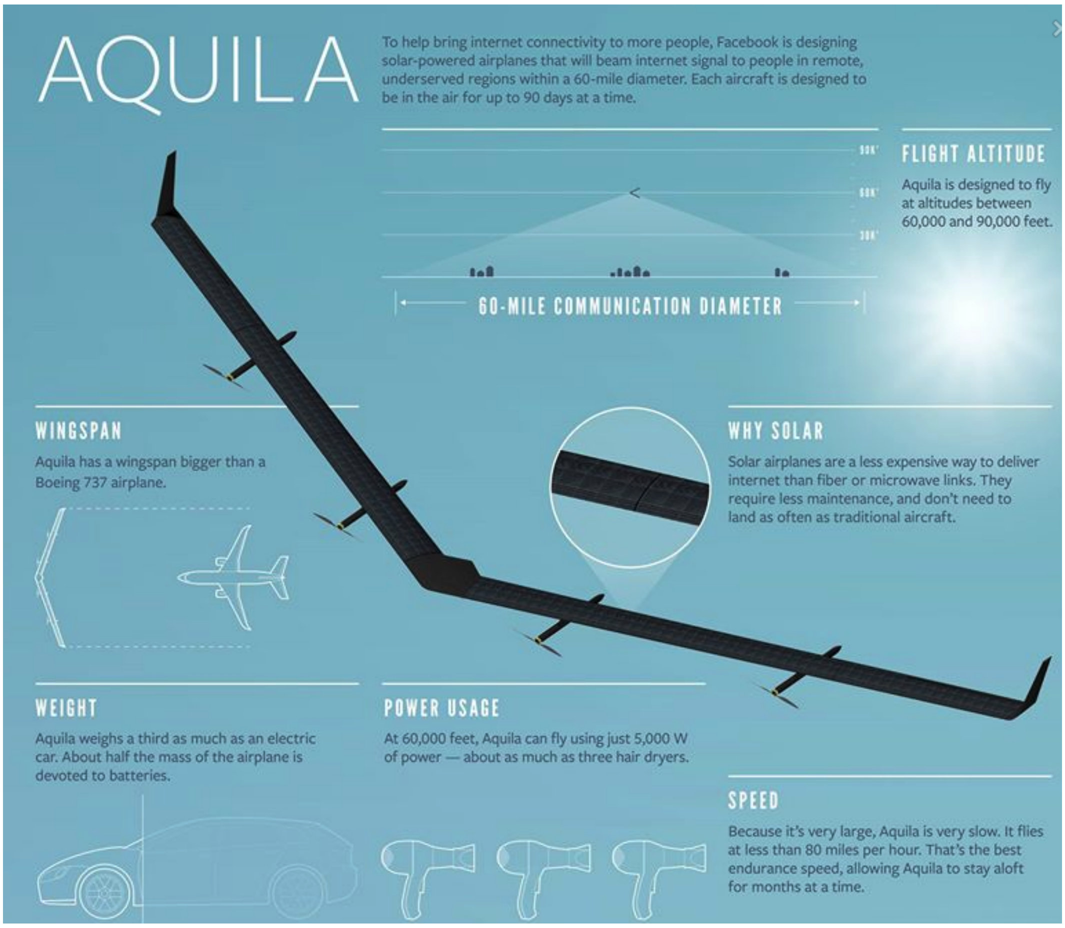

Figure 2.13: Facebook "Project Aquila" [75]

During the testing process, the team has successfully worked and designed unique features to the Aquila project. For example, the takeoff and landing gear are designed differently to the traditional style, making Aquila planes to takeoff on autopilot. Other features of the Aquila project in terms of how it is designed, includes an aerodynamic model which enables Aquila to operate in both cold, warm, thin, thick air and at high and low altitude [75]. Another feature is the battery and power performance which is intended to be fully powered by solar. The Aquila project will have a full time autopilot and this project has been tested under real-world conditions meaning that the plane will be able to respond to wind, turbulence and vertical gusts weather conditions.

Some of the challenges as mentioned in [76] which Project Aquila faces includes getting enough sunlight, as the airplane needs enough energy to operate. Therefore it must collect sufficient sunlight during the day to operate for a full 24 hours. Aquila requires approximately 5000 W of power to be able to work. Secondly, in relation to the batteries, Aquila requires a battery which can store lots of energy to last the plane a long winter night. Thirdly, the size and speed of the plane. Aquila has a wingspan similar to that of a commercial airliner but much lighter in weight, making the design process challenging.

Lastly, the issue relating to the cost of a new project. In order for the project to be successful and economically viable, an alternative solution to the current networking infrastructure, the new design must be developed to by-pass the traditional design.

Table 2.5: Facebook "Project Aquila"

Facebook "Project Aquila"	
Equipment	Solar panel powered drone with high,tech drone aviation
Control	The drone's location & movement can be controlled with precision.
Flight time	Drone can stay in air for a month, plans are to extend it to an year
Signal	Uses Infrared Lasers for data, connection speeds nearing the speed of fiber optic cables.
Landing	The Drone has the ability to glide down for safe landing in case of failure.
Placement	Hovering of drone over predefined area to beam down the internet.
Flying Hight	60-65k altitude range in the,stratosphere

2.13.5 The Use of drones to deliver medicine in Papua New Guinea

Access to healthcare in Papua New Guinea (PNG) is limited by geographical and logistical challenges. This has led Medecins Sans Frontieres (MSF), the first humanitarian organization to test the use of drones to deliver packages in this part of the pacific. Using drones to deliver medical supplies to some remote areas has changed the lives of local people in this part of the world. To MSF, the main problem is related to the transportation of diagnostic samples from remote heath centers around the region to a designated laboratory location in the shortest amount of time possible.

Geographically in this case, health centers in this part of the region are scattered between the range of 24 km to 134 km from the central hospital. There are 6 health centers and 3 of these are accessible only by boat and the others are sometimes accessible via plane and on foot. The Kerema hospital is the central hospital equipped with the proper medical tools including a laboratory with functional microscopy and GeneXpert to analyze samples.

Figure 2.14: Drones used in Papua New Guinea to deliver medical supplies [77]

The drone used in this case is able to carry a payload of 200-500 grams and operated in winds of up to 36 km/hour. The drone can also fly autonomously and beyond visual line of sight. Take-off and landing requires a location clear of obstacles for the vertical take-off. The deployment site requires a minimum cellular connectivity with General Packet Radio Service (GPRS) as well as access to electricity even for a few hours to recharge the batteries. The flight path for this mission is generated using a computer software [77].

Figure 2.15: Flight path for the drones used to deliver medical supplies in Papua New Guinea [77]

In this case study, the benefit from using drones is clearly visible in terms of the increase in delivery time. When using drones, 55 minutes in total to complete the route that covers the aerial distance of 42.5 km as indicated in figure 2.15 versus the 4 hours' drive by car.

2.14 Rules and regulations for UAVs

As technology increases, so does the need for regulators to take control of how these technologies are being used. Drones themselves have become a hot debate, due to its mobility pattern to cover certain areas where humans are at risk. For safety and privacy concerns, both regulators and those using drones are faced with challenges to control such activities [78]. Talks about the need for clear and high-regulated management of navigation and airspace for drone application [22] and [79] .

There are two main categories in which the rules and regulations fall in [26]. Firstly, to consider the issue of different categories of platform commonly used for aerial wireless services such as aircraft, balloon, airship, helikites and drones.

The other factor is the type of control method used for each platform such as a remote piloted aircraft, tied up helikites etc. The author also provides the following factors to which the legislation can be drawn from. Another issue to consider is the flying altitude of the craft. In certain countries, a license is not required for any type of aircraft when flying below certain altitudes, such as below 120m in Australia, this is further discussed in [26].

One other important point to consider is the region in which the flying craft will be operated, such as, urban or regional areas, or near to airports etc. Another issue to look at is the current environment situation. For example, some countries like Australia will not allow drones to fly over or near areas where there is fire, or traffic accidents etc. Rules and regulations are required and they do exist in these situations to assure safety of flights, people and their environment.

2.15 Conclusion

In the event of a natural disaster, communication is vital to ensure optimum level of safety is achieved. Drones or UAVs are the finest options because of their flexibility, versatility, easy installation and relatively low in operating costs. Thus far literature has shown potential usage of UAVs which ranges from surveillance, search and rescue, filming, infrastructure, agriculture, delivery, military activities and many more.

Furthermore, UAVs come in different forms and sizes. The design of a UAV determines how and what they are used for. This research states two main categories in which UAVs are classified into. One is according to the performance specification which includes performance characteristics such as the UAVs weight, engine type, payload, power load, flight time and cost. The other specification is to what it is assigned for or its mission. Our focus in this research is to examine the effectiveness and benefits of operating a heterogeneous network (HetNet) which is a combination of both macro and micro base stations. The aim of having to operate this mix advance LTE networking system, is to gain spectral efficiency per unit area and to optimize coverage in the process.

Chapter 3

Research Methodology

3.1 Introduction

In this research, simulation studies have been conducted using Matrix Laboratory (MATLAB). MATLAB is a programming language that allows users to do matrix manipulations, plotting of data and functions and operations of algorithms are just some of the functions. The program uses computer languages including C, C++, and Java among others.

The purpose of conducting the simulation is to explore the mobility of UAVs by using brute force search to optimize the locations of an Unmanned Aerial Base Station (UABS). The location or position of the drone is important, as it will provide better coverage when it is placed accordingly. In this research, we chose to use brute force search, because it is relatively easy compared to other techniques such as genetic algorithm.

3.2 Research Design

The literature review in the previous chapter has proven that UAVs are becoming the promising technology that provides aerial communication in places and situations that are unstable or considered dangerous for humans. While this research focuses on the use of drones to provide communication in the event of a natural disaster, one of the issues of concern here is the capacity of data traffic or amount of data coverage that the Unmanned Aerial Base Station (UABS) can handle at any given time after the occurance of a natural disaster.

Looking closely at our case study, we consider an ideal communication channel in the event of a natural disaster in the Cook Islands. We are faced with the issue of extremely high cost for a broadband networking system and other closely related problems. The high cost for broadband is the greatest barrier to end users of mobile technology due to various contributing factors including geographical and logistical challenges.

3.3 The Cook Islands

The Cook Islands is a group of islands named after Captain James Cooks who discovered and visited the islands between 1773 to 1777. The islands are divided into two groups, 6 of which are mainly atolls in the northern group islands and 9 islands in the southern group largely volcanic. The 15 islands are spread out over 2 million square km of the great Pacific Ocean [80].

Figure 3.1: The Cook Islands [80]

Table 3.1: Population for the Southern and Northern Group Islands

Resident Population for the Northern and Southern group Islands			
Location		***Location***	
Southern Group Islands	***Total***	**Northern Group Islands**	***Total***
Rarotonga	10,572	*Palmerston*	60
Aitutaki	1,771	*Pukapuka*	451
Mangaia	562	*Nassau*	73
Atiu	463	*Manihiki*	238
Mauke	300	*Rakahanga*	77
Mitiaro	189	*Penrhyn*	213

As modern Pacific people, Cook Islanders have a blend of western influence and ancient Polynesian heritage. Rarotonga the capital is also the largest and most populated in the group of islands. Aitutaki is the second most populated and is popular with tourists mainly for its beautiful lagoon. The rest of the islands in the northern and southern groups are less populated but regularly visited by government officials to maintain national control. Table 3.1 shows the total population for all islands in the

Southern and Northern Groups according to the last national census 2011.

Table 3.2: Cook Islands Residents Census 2001-2011

Census Residents Population 2001-2011			
	2001 Census	**2006 Census**	**2011 Census**
	Total	***Total***	***Total***
Cook Islands	14,990	15,324	14,974
Rarotonga	9,424	10,266	10,572
Southern Group Islands	3,777	3,729	3,290
Northern Group Islands	1,789	1,369	1,112

3.3.1 Geographical layout of Rarotonga

The capital island of Rarotonga has a total circumference of 32 kms, and the highest point is measured at 658 meters above sea level. The interior of the island is covered with mountain terrains and thick tropical rain forests, making it harder for locals to build and live in this area of the island.

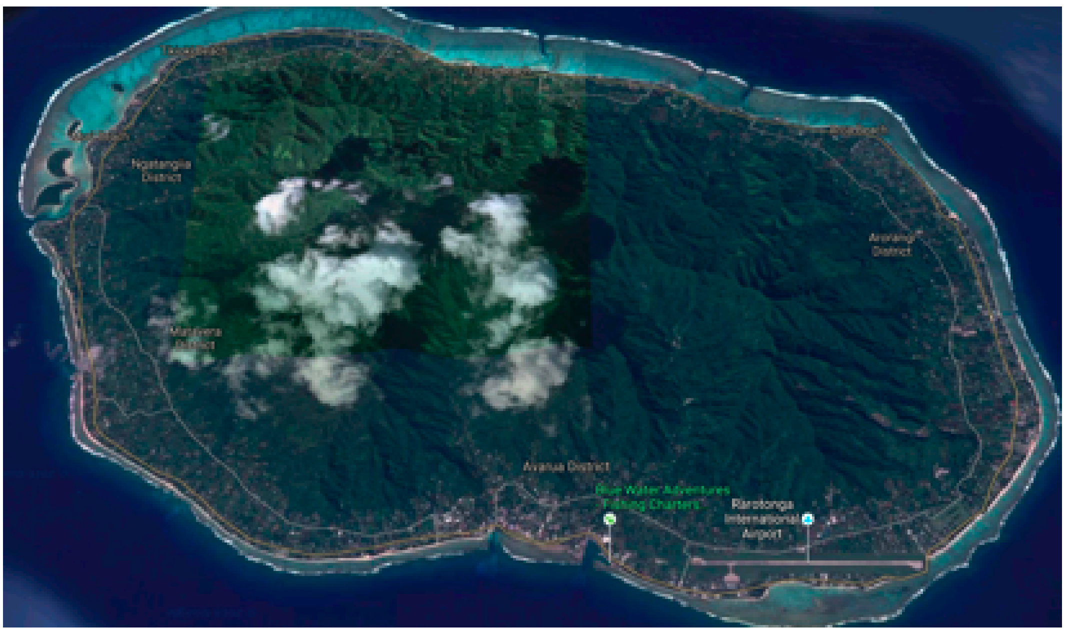

Figure 3.2: The capital of the Cook Islands (Rarotonga)

3.3.2 Population statistic and the living enviroment

The most populated area is along the coastline, and this is the case right around the island. The main village of Avarua is located on the northern side of the island. This is where most of the government departments are situated, as well as the main Internet Service Provider (ISP) Bluesky. The population of the main island of Rarotonga is about 10,572 as per the 2011 national census report [81].

Figure 3.3: Populated area of Rarotonga

Table 3.3: Population for the village on the Island of Rarotonga

Resident Population for the village on the Island of Rarotonga	
Location	***Total***
Rarotonga	**10,572**
Kiikii-Ooa-Pue	1,263
Tupapa-Maraerenga	451
Takuvaine	674
Tutakimoa-Teotue	270
Avatiu-Ruatonga-Atupa	950
Nikao-Panama	1,404
Ruaau-Arerenga	1,171
Akaoa-Betela	739
Murienua	730
Titikaveka	1,211
Ngatangiia	785
Matavera	969

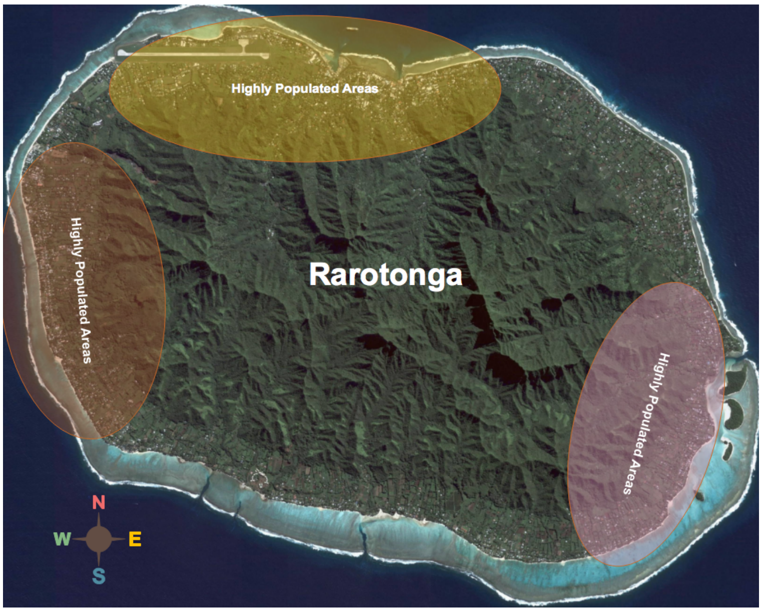

Figure 3.4: Densely populated areas

3.3.3 Current cellular network infrastructure

The current cellular infrastructure is highly controlled and dictated by the only ISP Bluesky. The Internet Service Provider has 4G technologies in service for people on the island. The Cook Islands was one of the first in the South Pacific to take up the O3b Networks and provide its services to customers. With the availability of O3b network, customers are able to enjoy ultra-low latency and fiber like speed. However the network did very little to the current high cost of broadband [82].

What this means for the end users of mobile technology on the island, including, emergency first responders is to either follow the existing networking structure, meaning dealing with the increasing cost or look for other cost effective alternatives.

Furthermore, on the design-networking infrastructure, the present technology currently being used by emergency first responders on the island, is the Land Mobile Radio (LMR) that provides reliable voice technology. On the other hand, using broadband technology in Public Safety Communication (PSC) system will offer more benefits such as voice, video streaming and data technology. The latter option will be the ideal solution for the Cook Islands.

Figure 3.5: Locations of cell towers around Rarotonga

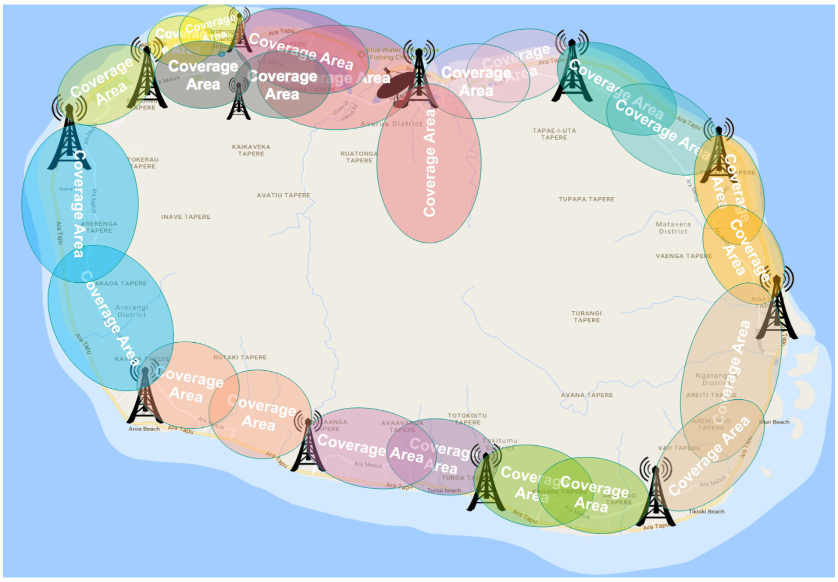

Figure 3.6: Locations of cell towers around Rarotonga and the area of coverage

There's a total of 12 cell towers at specific locations right around the island of Rarotonga. These cell towers are placed at their current positions to cover as much ground area as possible. Figure 3.5 shows the locations of the cell towers along the costal line where it is most populated. According to Bluesky, with the existing cell towers, the island of Rarotonga is about 90% covered allowing broadband connections to be available to all users except if the user is located further inland.

All the 15 islands in the Cooks have aerial communication structure in place however Rarotonga and Aitutaki are currently on 4Gs while the rest of the outer islands have 2Gs. The total number of prepaid mobile users according to Bluesky is around 16,000 for the whole of the Cook Islands. Some users of prepaid mobile will have more than one active sim card making the total number of active user of prepaid service to be higher than the actual population of the Cook Islands.

Furthermore, Bluesky as indicated that in the event of a natural disaster and a cell tower is destroyed, they only have on hand parts to repair one fully operational cell tower. Therefore if more than one cell tower is destroyed, the priority in terms of which cell tower to be repaired first will be the cell tower located along the town area where most government departments and businesses are situated.

Figure 3.7 below shows two possible channels of communication, one by using cell towers and the other is using UAVs as indicated by network 1 and network 2. In the event when a cell tower is destroyed, the alternative UAV network is used.

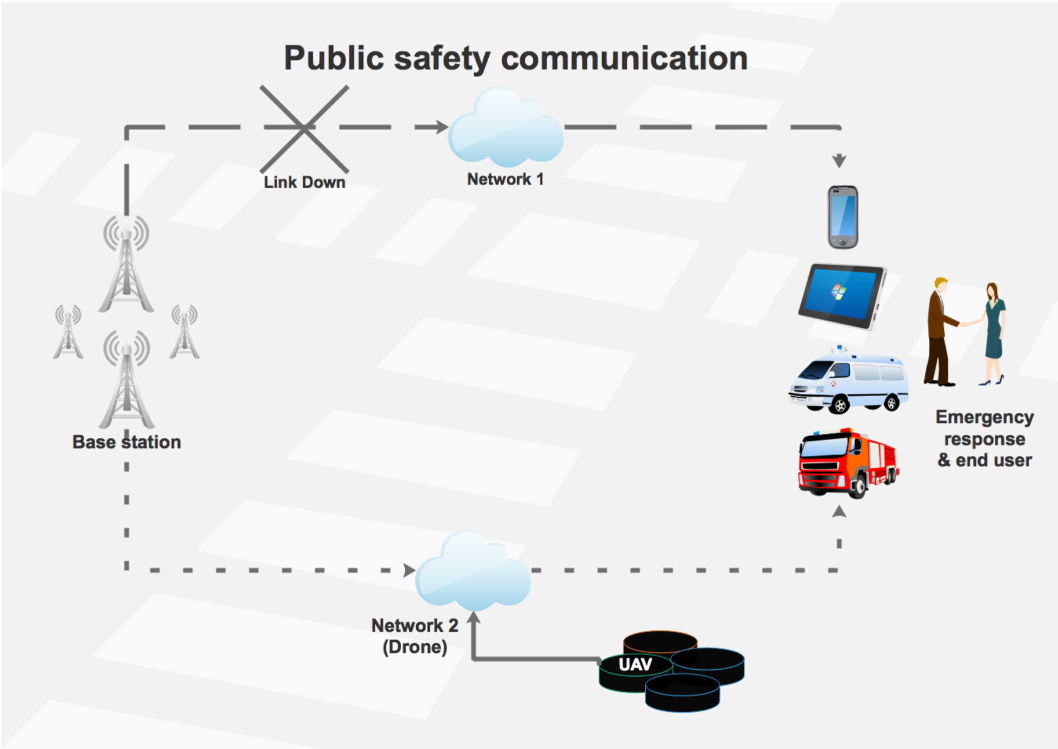

Figure 3.7: Public Safety communication

3.3.4 Tourism

The Cook Islands is known for its tourism reputation and the number of visitors arriving on our shores have increased in the past years. Figure 3.8 shows the figures relating to the number of visitors arriving into the Cook Islands in the past 3 years. On a typical year, the months of June to October are the busiest period where visitors number increases and July as the most preferred month of travel by many visitors. An average temperature in the Cook Islands between the month of June to October is around 18 average low to 26 average high degrees Celsius, a typical winter and cooler temperature. Summer is around November to early April [81].

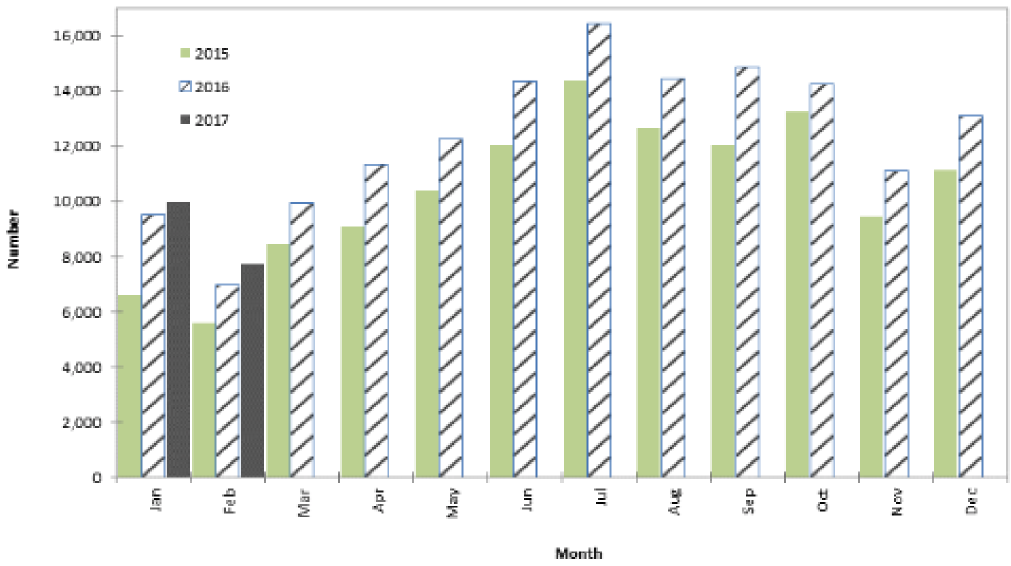

Figure 3.8: Visitor numbers to the Cook Islands [81]

Figure 3.9: Lovely beach on Rarotonga [80]

Figure 3.10: Main road of Rarotonga [80]

3.3.5 Weather pattern in the Cook Islands

The climate in the Cook Islands varies and changes from year to year, following the natural climate pattern the EL Nino-Southern Oscillation, which occurs across the tropical Pacific Ocean [83]. Between November and April is the common period to which a tropical cyclone affects the Cook Islands. The number of cyclones differs from year to year, and the islands within the Cook Islands have come across some of the worst tropical cyclones in the past. While in some years the country may have one or none in some seasons, the worst year so far was in 2003/04 where Rarotonga alone experienced a total of 6 tropical cyclones within that period [84].

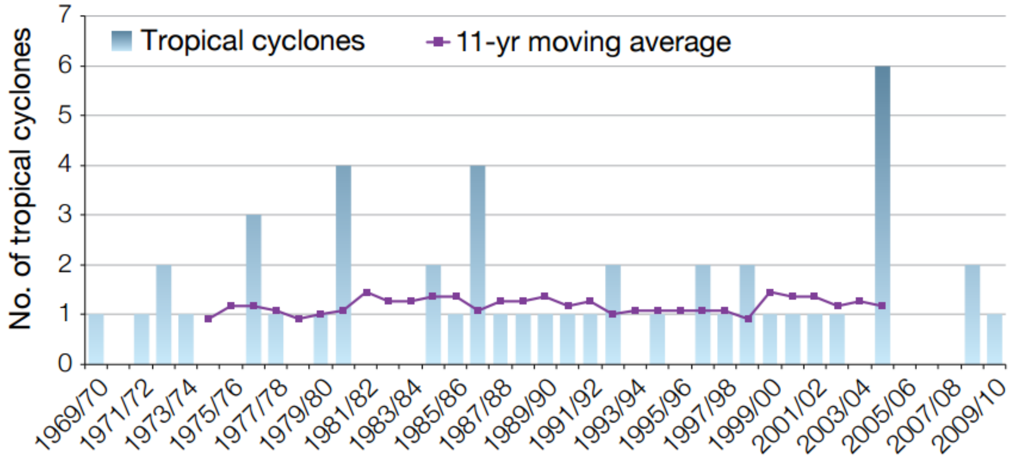

Figure 3.11: Tropical cyclones that hit the Cook Islands in the last 50 years [83]

3.3.6 High cost of fuel

The cost of fuel is extremely high as this commodity is imported. There is a huge demand for fuel on the island as diesel generators generate the main source of electricity. The current fixed based station located at designated areas across the island relies heavily on the diesel-generated electricity. In the past years till present, the government is pushing the country towards a 100% use of renewable energy that will dramatically reduce the cost of electricity, but at this stage, more details on the subject is beyond the scope of this research.

3.4 Disaster Management Plan for the Cook Islands

The Cook Islands has in place a National Action Plan for Disaster Risk Management dated 2009-2015, for more information refer to [85]. There is currently an ongoing process on the newer version of the plan which according to the head of the Emergency Management Cook Islands (EMCI), is most likely to be completed very soon. In terms of the communication process during and after a natural disaster occurence, the main control of communication lies with the EMCI, assisted by the local Cook Island Police

Department, the Red Cross, and the Health Department. At present the EMCI uses satellite phones in the event of a natural disaster to communicate with other agencies around the island. The common procedure taken by BlueSky when the wind reaches certain strength that is around 45mph and over, they will lower the antenna for safety purposes. Meaning that only emergency agencies will have clear line of communication via satellite phones while most mobile users will experience poor connection or no connection at all. This is also the procedure taken on other islands in the Cook Islands as further discussed in [86].

To have a clear picture of the procedure in which the people on Rarotonga are required to do in the event of a natural disaster, the following graph shows evacuation centers located around the island where people are expected to report to [87].

Table 3.4: Evacuation centres on Rarotonga

Evacuation centres on Rarotonga		
Village	**Location**	**Phone number**
Arorangi	CICC Sunday School Hall	Ph: 22331
	Betela Meeting House	Ph: 21888
Te Au O Tonga	Avarua Primary School	Ph: 27230
	Saint Joseph School	Ph: 26111
	Catholic Hall	Ph: 20338
Nikao	Tereora College	Ph: 23820
	Nikao Hall	Ph: 23220
Matavera	Matavera Sunday School	Ph: 23941
	Matavera Catholic Hall	Ph: 23220
Ngatangiia	Ngatangiia Sunday School	Ph: 26069
	Muri Meeting House	Ph: 20317
	Ngatangiia CICC Hall	Ph: 26070
Titikaveka	Titikaveka College	Ph: 23015
	Kent Hall	Ph: 20316

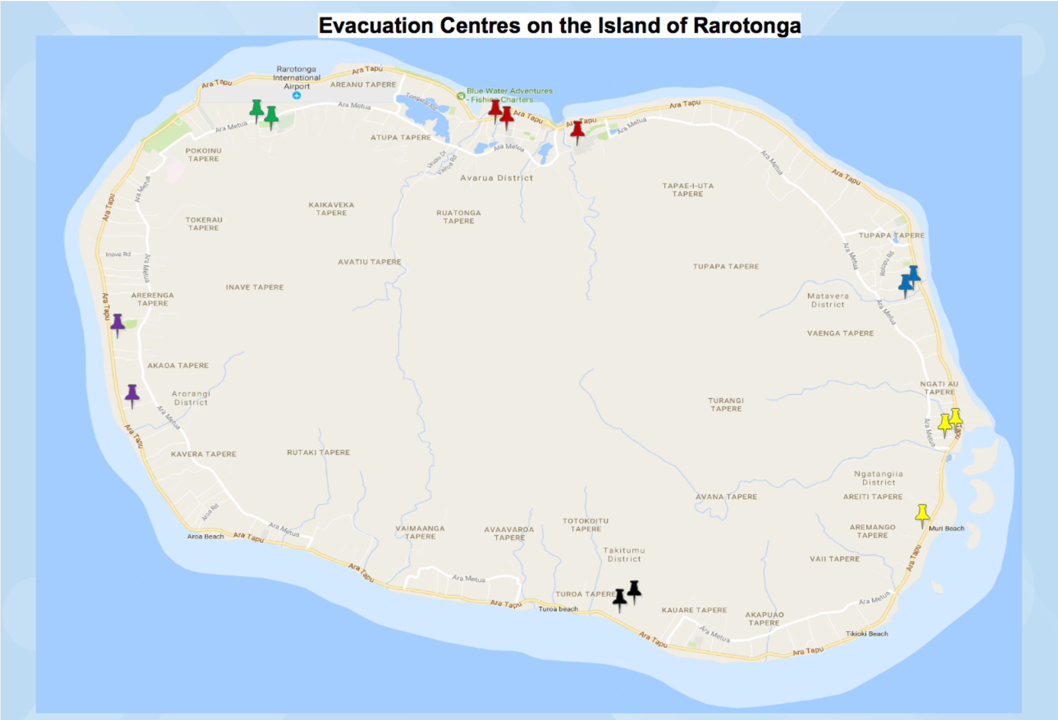

Figure 3.12: The Island of Rarotonga evacuation centres location

3.5 Research question and sub-questions

How to effectively use UAVs to optimize communication coverage in the aftermath of a natural disaster?

1. How can we improve the quality of communication required by emergency first responders in the event of a natural disaster?
2. How to maximize the performance of UAVs used as UABS in the event of a natural disaster?
3. At what level of performance would you consider safe coverage is achieved?
4. How can we improve the level of broadband coverage in the aftermath of a natural disaster?
5. Why do we use multiple UAVs rather than one UAV as base stations and what

are the advantages and disadvantages in applying this method?

6. How much will it cost to use UAVs as UABS in temporary situations such as in the event of a natural disaster?

3.6 Research plan

This research involves a couple of steps in which studying and reading related literature and doing analysis on the readings comes first. It is very important to create a better understanding and broader knowledge on the topic of Drones or UAVs. Secondly comes the process of conducting the simulation. This is the critical part of the research, the ability to run the simulation, understanding the coding, analyzing results, and doing other steps involved in running the program MATLAB, determines the overall effort into this research. Lastly comes the consuming time of writing up the full report. This part of writing the report is done in conjunction with the first two steps of the reading and simulation.

3.7 Data requirements and analysis

In this section of the chapter, we will discuss the different stages of data sources that form parts of this research. We first looked at what source of data is required for the research. The second step is to discuss how well we performed in producing the required data. This process measures the time in which data is processed thus far. It also describes how we can improve data processing time in future works. Thirdly we discuss the different types of methods or techniques used in collecting the data required. During this phase, we get to do some testing on the data collected. The last step is, analyzing the data collected. The result of this analysis will determine how well we answer our research questions.

The four different phases of the research are further discussed below:

3.7.1 Phase 1: Data creation

In creating data for this research, we looked at a couple of factors that helped in choosing the most appropriate information used in any part of the research plan to produce preferred results. These factors are classified into two categories, one of which is the general and supporting data group and the other as direct and specific data group.

In the first grouping, we based our choice of data selection on materials such as related information to the chosen topic. For example, we looked at general information about UAVs, the different types of UAVs and how they work. We also conducted literature review on issues relating to the changing weather conditions including the subject on Global warming and climate change.

The second method is more direct and specific to the chosen topic. At this point a direct approach considers information or data used in the simulation. As this research is based on a case study, the data or information at this stage becomes more specific to the Cook Islands. For example, we consided specific weather information relating to the Cook Islands, rather than to the rest of the world. We also consided specific measurements on the landmass of Rarotonga. The collection of specific information have formed part of the database used in the simulation.

3.7.2 Phase 2: Data processing

In this section, data processing has two parts. As mentioned above, the first step in creating a database is to form general information background to the study and looking at information that are more directly related to the case study. The process of conducting a literature review provides the data needed in this research. The second stage of data processing is directly related to the simulation. In the simulation, we consided two scenarios relating to public safety communication, where emergency first responders will carry this out.

In describing the simulation process, we started by assuming that all base stations are located randomly according to the Poisson Point Process (PPP). Before we made any other assumption, we evaluated the capacity and throughput coverage. The second step in the process is to randomly remove Base station (BS) points that represent a natural disaster. Then we examined the changes that represent the impact of damage to the infrastructure, and compare the capacity and coverage performance to the previous stage. In the third step, we created a picture that imitate the deployments of new UAVs during the aftermath of a disaster and study the capacity and coverage performance. An important part of this simulation is the ability to choose reliable parameters to be used in the two separate scenarios, and the ability to understand the formulas used.

3.7.3 Phase 3: Data collection

This section describes the method used in collecting the data. The research relies heavily on how well the literature review is conducted. Part of this research involves conducting a simulation and is important to have access to reliable information. The information will determine the values to be used as part of the parameter settings, as we conduct the simulation. The simulation used is a mathematical experiment to find the optimal placement of an UABSs that will potentially bring more benefits to the network.

Taking a closer look at what sort of information we may need to initiate the simulation, we use the following parameter settings produced out of MATLAB:

Table 3.5: Matlab simulation parameter

Parameter settings		
Features	***Values***	***Description***
lambda	4	MBS density (per km^2)
lambdaUE	100	*UE density (per km^2)*
LenSimArea	4.2686	*Length of the simulation area (in km)*
P_mac_dBm	46	*Macro Tx power (in dBm)*
P_uav_dBm	30	*UAV Tx power (in dBm)*
K_dB	-11	*Attenuation due to geometrical parameters of antennas (in dB)*
Number of UAVs	4	*Total number of available UAVs*
PercDestroyMBS	90	*Percentage of MBSs to destroy*
HeightMBS	0.03048	*Height of the MBS (in km)*
HeightUAV	0.12192	*Height of the UAV (in km)*
PLE	4	*Path lost exponent*
PlotCovArea	1	

The above table (3.4) is the simulation interface that shows some of the areas in which we needed to find values for. Among the most important measures, we looked at the density of Micro base station (MBS), the density of the user equipment (UE) and determining the length of the simulation area. The total number of available UAVs to be deployed and the need to indicate what percentage of MBSs destroyed as well as determining both the heights of the MBS and the UAV.

3.7.4 Phase 4: Data analysis

The process in which data is analyzed comes in many stages. As mentioned earlier in phase 2 of this section, data is analyzed after every testing step conducted in the simulation. While working with different measures of parameters in each individual scenario, data is always analyzed before moving onto the next set of different parameters. This process makes this part of phase 4 the longest, as trial and error is carried out, to increase the chances of producing reliable results.

At the end of this process, an overall data analysis is conducted to determine the final actions. At this point, we also discuss the impact of the simulation on the overall performance of the drone. The purpose of conducting this simulation and the result of the data analysis will help in answering the research questions.

3.8 System Modeling

An important part of this research process is looking at the different equations that are used in producing the results. There is a total of 12 equations, and these are further explained below:

$$S(d_{nm}) = \frac{P_{tx}G}{d_{nm}^{\delta}} \tag{3.1}$$

where P_{tx} is the transmitting power of all the Macro Base Stations (MBSs) and G represents all accounts for the geometrical parameters used, such as transmitter and receiver antenna heights. The δ represents the path-loss exponent (PLE).

When considering the limited network interference, we assume that the receivers thermal noise power when compared to the interference power is insignificant, therefore we express the SIR at UE n to be as follows:

$$\Gamma_n = \frac{S(d_{nm})}{\sum_{i\in M, i\neq m} S(d_{ni})}, \tag{3.2}$$

where M is the set of all MBSs and d_{ni} is the distance between the UE and the MBS denoted by n-th the number of UE and i-th is the MBS.

Furthermore, we are able to determine the total interference power at user equipment (EU) from all the MBS except the MBS currently serving denoted by MBS m. The denominator in the above equation 2 represents this total interference power.

The following third equation determines the spectral efficiency (SE) of a macrocell user equipment (MUE). By using Shannon capacity formula and for simplicity noticing the round-robin scheduling, we can express the equation as,

$$Cn = \frac{log_2(1 + \Gamma_n)}{N}, \tag{3.3}$$

where the denominator N represents the number of MUEs in the macrocell.

Equations 1 to 3 represents factors that can be determined and calculated in a scenario and situations before any natural disaster occurs. In other words, the parameters are relatively normal and depicts the current communication network of any particular location.

The following equations are used to determine the coverage improvement when using UABSs. At this stage, we assume that a natural disaster has occurred, and that communication network is disrupted hence the need for alternative temporary communication solution. In this scenario, we are using UAVs as UABSs and form a heterogeneous network (HetNet) where both macro base stations are used and micro base stations deployed to form an advanced network and improve connectivity.

Unlike macro base stations which are static and remain in one location, the deployment of UABS rather works dynamically causing it to move around and allowing its location to adjust and cater for the also dynamic nature of its receiver UE. The dynamic characteristics of UABSs makes its physical location easily adjusted to get the best networking performance and optimization coverage for any given scenario.

At this stage, in our scenario, we have formed a HetNet where both the MBS and UABSs are used forming a two tier of BSs. We also assume that both these base stations share a common bandwidth and that there is a wireless backhaul links with large capacity connected to the UABSs. These links use a different frequency bandwidth than the access links.

Let's consider the average received signal power in which the UE n experiences the SIRs. For simplicity, let the nearest MBS m at a given distance (d_{nm}) to be it MBS of interent (MOI) and also the nearest UABS u at a given distance (d_{nu}) to be its UABS of interest (UOI). With this information we can express the average received signal power for each of the MOI and UOI as follows:

$$S(d_{nm}) = \frac{P_{tx}G}{d_{\delta_{nm}}}, S_{uv}(d_{nu}) = \frac{Puv_{tx}G_{uv}}{d_{\delta_{nu}}} \tag{3.4}$$

where Puv_{tx} is the transmitting power of UABSs and the G_{uv}represents all accounts for the geometrical parameters used such as transmitter and receiver antenna heights. With the above formula, we can calculate separately the average received signal power from the MOI and the UOI to the UE.

Taking into account the above equation 4, we are able to determine the average received signal power from the MOI only to the UE with the following formula

$$\Gamma_n = \frac{S(d_{nm})}{\sum_{i\in M, i\neq m} S(d_{ni}) + \sum_{j\in U} Suv(d_{nj})}, \tag{3.5}$$

where U is the set of all UABSs and the distance of i-th UE to j-th UABS is denoted by (d_{nj}).

The following equation below expresses how the average received signal power from the UOI only to the UE is determined.

$$\Gamma_n^{uv} = \frac{S_{uv}(d_{nu})}{\sum_{i\in m} S(d_{ni}) + \sum_{j\in U, j\neq u} Suv(d_{nj})'} \tag{3.6}$$

also where U is the set of all UABSs and the distance of nth UE to j-th UABS is denoted by d_{nj} .

At this stage, we are able to determine the total interference power at the UE with the denominators in both equations 5 and 6. When combining the average received signal power from both the MOI and the UOI and taking into accounts the different geometrical parameters such as the transmitter and receiver antenna heights, will then an arbitrary UE experiences the SIRs.

The equation below illustrates the association process in which the UE perform a cell selection where in this case chooses the MBS of interest (MOI) as the value for MOI denoted by Γ_n is greater than Γ_n^{uv} The following is expressed as follows:

$$if(\Gamma_n >_r \Gamma_n^{uv}) SelectMoI : \tag{3.7}$$

Where $_r$ is the range expansion bias (REB).

Equation 8 is similar to equation 7 however this time the UABS of interest (UOI) is greater than the MOI or the MOI is less than UOI and therefore the UE will choose the UOI. The following association process is expressed as

$$if(\Gamma_n >_r \Gamma_n^{uv}) SelectUoI : \tag{3.8}$$

Where $_r$ is the range expansion bias (REB).

The following equation 9 and 10 represents the spectrum efficiency (SE) of a macrocell of user equipment (MUE) as well as the SE of the unmanned aerial base station (UABS) cell of user equipment (UE) denoted by UUE respectively expressed as

$$C_n = \frac{log_2(1 + \Gamma_n)}{N} \tag{3.9}$$

$$C_n^{uv} = \frac{log_2(1 + \Gamma_{uv} n)}{N_{uv}} \tag{3.10}$$

where N_{uv} is the number of UUEs in the UABS-cell.

Equation 11 as expressed below is used to calculate the 5th percentile (SE) when a Genetic Algorithm (GA) is used to optimize the locations of UABSs however in our case, for simplicity, brute force search is used to optimize placement of UABS in a way to maximize the 5th percentile throughput of the network. In this thesis, the 5th percentile represents a fitness function of throughput coverage over the whole network also applied with Genetic Algorithm (GA). Similarly, brute force search is used to maximize the 5th percentile rate.

$$P_k = \frac{f_k}{\sum K_k = 1 f_k}, \tag{3.11}$$

In the above equation, f_k is the fitness value of chromosome K and $_k$ is the number of chromosomes in the population.

The Shannon's capacity equation expressed below is a formula also mentioned in equation 3 earlier. It is used to work out the spectral efficiency (SE) of a macrocell user equipment (MUE) and considering the round-robin scheduling.

$$\Gamma_n = log_2(1 + S_n)/N_{ue} \tag{3.12}$$

Furthermore, the formula is used to calculate the throughput coverage where S_n is the signal-to-interference ratio for the $_nth$ UE.

3.9 Limitation to the research methodology

The problem in conducting the simulation MATLAB in this research is that it only provides one specific task of locating an appropriate position for the Base Station (BS) that will enhance the capacity and throughput coverage. Other features of the drone or UAV such as the required weight, the control function, and the general design requirement are not measured or looked at with the simulation MATLAB. Other measures will have to be conducted to address the issues that MATLAB is not able to address.

3.10 Summary

This research uses MATLAB to conduct the simulation as it is relatively cheaper compared to a real life experiment. This method of simulation has been proven reliable and cost effective. This has been used in many other researches mentioned earlier in this paper, including the project conducted by Facebook and Google, and many others. The purpose of the simulation is to explore the mobility of drones and find the optimal location of UABSs, using brute force search that provides the maximum level of throughput coverage over an area affected by a natural disaster.

An important task involved in the simulation is determining the values to be used for the parameter settings. As part of the research methodology, we looked closely at specific information on our case study about Rarotonga. We learnt that people on the island are living largely around the coastal areas, and making these areas our point of focus. Information such as the current design of communication infrastructure and the disaster management plan used on the island are all valuable pieces of information used in this part of the research work.

Furthermore, we used four phases of the research method to explain more on the level of work involved in this research work including data creation, data processing, data collection and data analysis. Lastly we included our system modeling where we discussed various equations used in this research. A total of twelve equations, including the Shannon's capacity equation, equation to calculate the 5th percentile, spectrum efficiency (SE), signal power and interference power.

Chapter 4

Simulation Studies

4.1 Introduction

The following chapter focuses on the research findings. As part of this research, we looked into two different types of environmental situations. One is public safety communication during the aftermath of a natural disaster. The other is considering a communication network in remote areas. The focus is on the former where we considered a severe type of natural disaster and based our simulation parameters to indicate such type of situational measures.

The figure 4.1 below is a typical communication network that shows the use of UAVs as dynamic base stations.

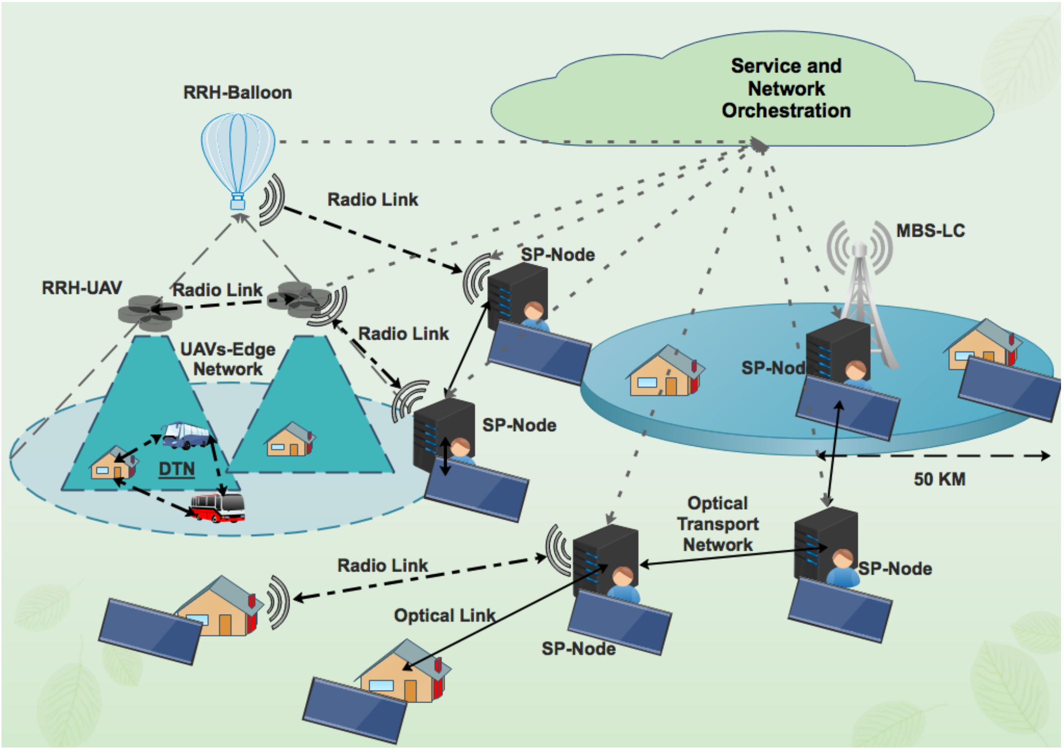

Figure 4.1: The use of UAV-assisted edge network for challenged network scenario (i) rural and developing area. (SP = solar powered, MBS= Macro Base Station LC = Large Cell, RRH = Remote Radio Head, UAV = Unmanned Aerial Vehicle, DTN = Delay Tolerant Network, NODE = Adaptable component used as micro edge/cloud server, BBU=Baseband Unit, SDN switch and optical router)

The focus is on the following public safety communication network in which a HetNet system is used. In this case, we needed a quick delivery of broadband connection, low in cost and an ubiquitous communication infrastructure.

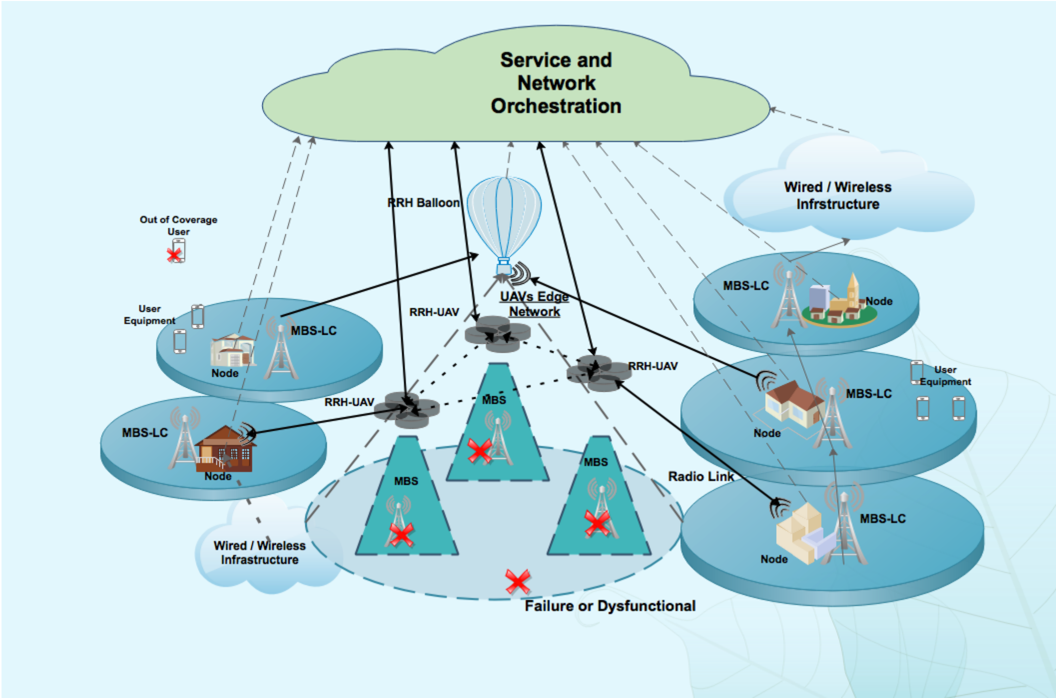

Figure 4.2: The use of UAV to assist edge network for challenged network scenario (ii) disaster and emergency scenario

4.2 Categorization of cyclone or hurricane

Before looking into our public safety scenarios, it is useful to understand how cyclones or hurricanes are categorized in order to assist in analyzing the parameters required to conduct the simulation. The table below provides details on the different levels of hurricanes commonly seen and likely to hit the Cook Islands as further discussed in [88].

Table 4.1: Category of Hurricane

Category	Sustained Winds	Types of Damage Due to Hurricane Winds
1	74-95 mph 64-82 kt 119-153 km/h	Dangerous winds with some damage to roof. Shallow rooted trees could come down. Damage to power lines, power outages.
2	96-110 mph 83-95 kt 154-177 km/h	Extremely dangerous winds, major damage to roof. Trees will be uprooted and block numerous roads. Near-total power loss.
3 *(Major)*	111-129 mph 96-112 kt 178-208 km/h	Devastating damage will occur: Homes may incur major damage. Trees will be snapped or uprooted, roads will be blocked. Electricity and water may be unavailable for several days or weeks.
4 *(Major)*	130-156 mph 113-136 kt 209-251 km/h	Catastrophic damage. Severe damage to homes, with lost of most of the roof structure. Most trees will be uprooted. Power outages may last months. Areas may be uninhabitable for weeks or months.
5 *(Major)*	157 mph or higher 137 kt or higher 252 km/h or higher	Catastrophic damage will occur. Homes will be destroyed. Fallen trees and power poles will be down. Power outages to most areas. Most area will be uninhabitable for weeks or more.

4.3 Simulation Studies

The simulation is conducted at aiming to find the best possible location of UAVs, to maximize coverage in a public safety communication situation. In this scenario, we applied different parameters to portray what might happen in the event of a natural disaster. As you will see further down in the chapter, the simulation provides different set of plots or graphs as a result of the set of parameters applied. In terms of parameters, we focus on areas such as the heights of UAVs, the number of UAVs deployed, and the path loss exponent (PLE). While the rest of the parameters remain constant or left at default values. These plots are discussed in details further below.

In the following simulation analysis, we considered a scenario example of a category 4 to 5 cyclone or hurricane, which are severe forms of natural disaster. We then considered the best possible solution in providing a reliable and capable public safety communication system which can be used in a hostile environment following the aftermath of a natural disaster. We need to remember that in such situations as this, an effective broadband communication system is vital. Especially to first responders who need to communicate to victims in affected areas, where communication mediums and networking infrastructure are likely to be damaged during a natural disaster.

In order to maintain a high throughput coverage in the network, the dynamic ability of UAVs that allows it to move freely and at any given height over a hostile area, makes this a powerful instrument. To demonstrate the potential gain in coverage when UAVs are used in a network, we further investigated how the throughput of the network can be improved with the optimization deployment of UAVs.

4.4 Investigating the heights of UAVs

4.4.1 The height of UAVs at 121.92 meters (400 feet)

As indicated below in table 4.2, the system parameters for the simulations were set to the following values to best illustrate our case study and a public safety scenario.

Table 4.2: System parameters for the use of 3 UAVs at a height of 400 feet

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	4
Height of UABs	121.92 meters or (400 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	3
PercDestroyMBs	70%

In figure 4.3 below, it shows the throughput coverage when the parameters are set at the given values stated above in table 4.2. It also represents a typical current flow of public communication system before any natural disaster happens. The red dots scattered on the graph represents the existing macro base stations within the area of concern. The green colored areas indicate the throughput coverage in which at this stage, dominates the area of concern meaning that coverage is relatively larger. The grey line is the cell boundaries and the white colored area represents an area with lower to no throughput coverage. For the user equipment (UE), the white area is a concern as signals are weak due to various factors including the distance of the UE from its nearest MBS, an overload of traffics on the MBS or due to the environmental factors that block out a clear line of sight including high buildings or mountains..

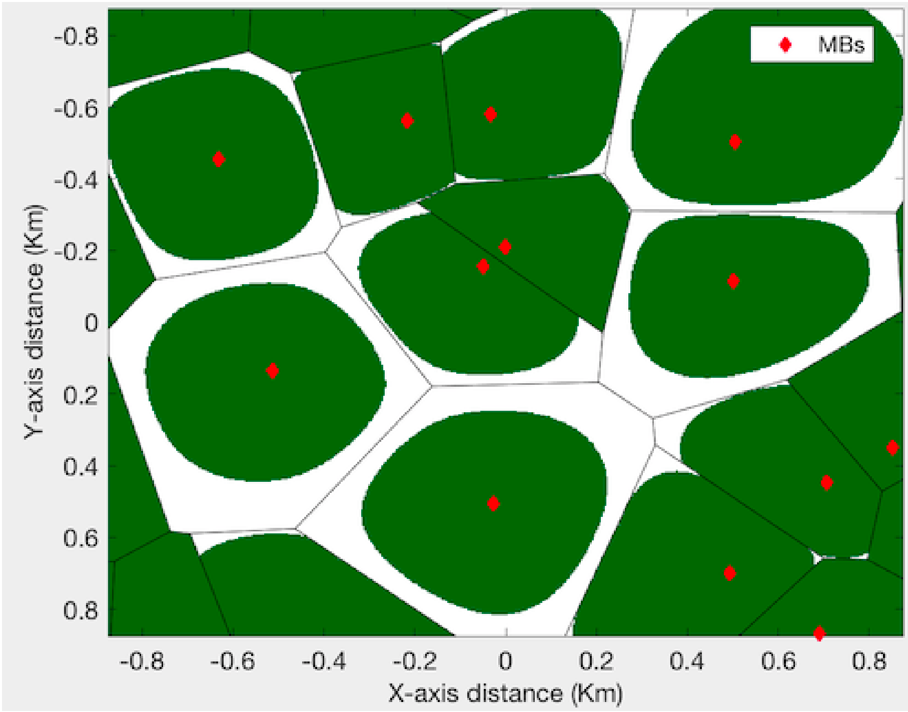

Figure 4.3: The image of the throughput coverage before an hurricane and the height of UAVs is at 121.92 meters

The figure 4.4 below depicts a situation where 70% of the existing macro base stations (MBS) are destroyed in the aftermath of a severe hurricane. When comparing it to figure 4.3 above, the red dots are less as these macro base stations are randomly being removed from the picture. As a result of this process, there is less throughput coverage in the area of concern as indicated by the larger white area. In this situation, the reality is that people in the affected areas are experiencing very low coverage or no coverage at all. This also affects the ability of first responders to reach casualties in the affected areas and to better coordinate the search and rescue efforts.

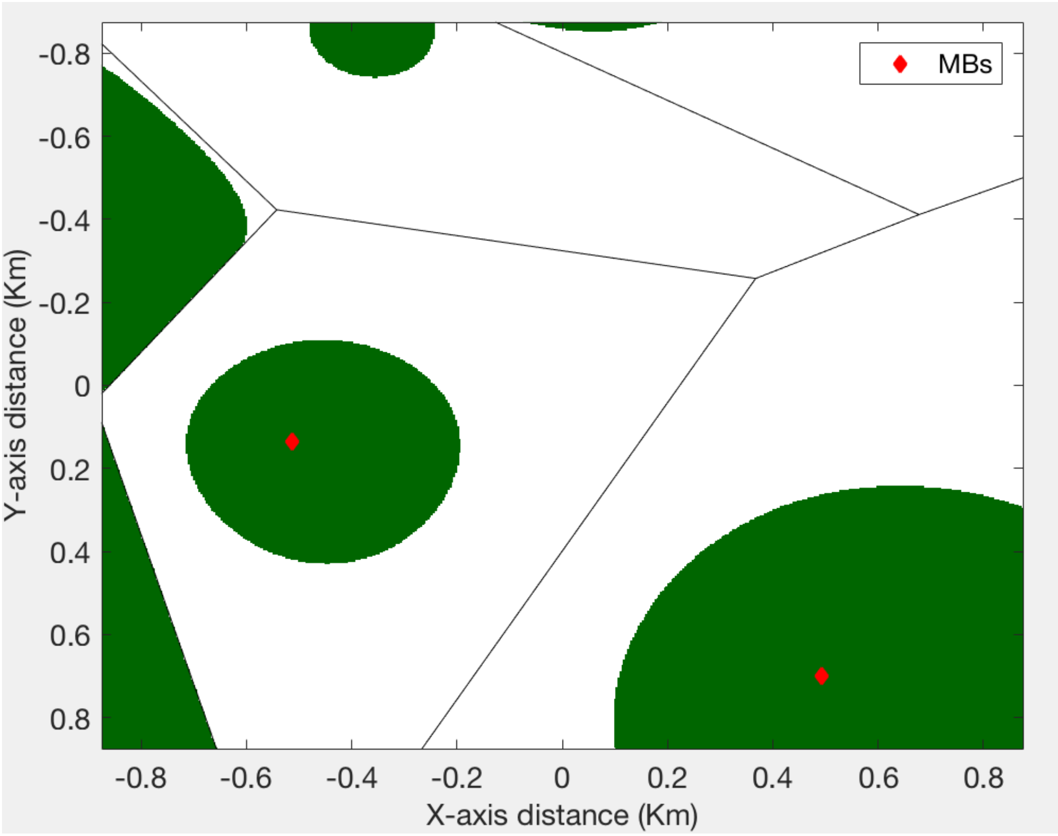

Figure 4.4: Image of the throughput coverage after a hurricane and 70% of MBs are destroyed

In figure 4.5 below, we introduced a total of 3 UABSs and deployed these out at optimized locations within the disaster zone by using brute force search. These UABSs are then flown up to a total height of around 121.92 meters equivalent to 400 feet. The pink cross shown in the graph corresponds to the location of the 3 UABSs and the gray colored areas represents the new throughput coverage.

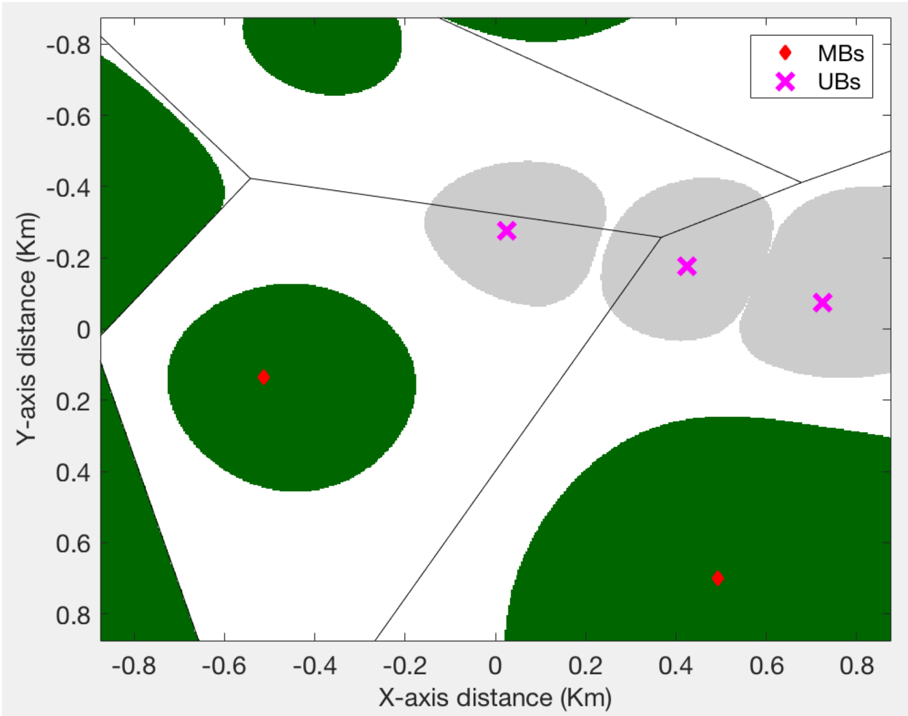

Figure 4.5: Image of the throughput coverage after an hurricane and 3 UABSs are deployed at the height of 121.92 meters or 400 feet

4.4.2 The height of UAVs at 243.84 meters (800 feet)

The following table 4.3 below shows another set of parameters tested, where the values of all parameters remain the same at default except the height of UAVs which had been increased from 121.92 meters (400 feet) to 243.84 meters (800 feet).

Table 4.3: System parameters for the use of 3 UAVs at a height of 800 feet

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	4
Height of UABs	243.84 meters or (800 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	3
PercDestroyMBs	70%

As a result of the above set of parameters, the increased change in height shows a decrease in the area of throughput coverage indicated by the grey area on the graph.

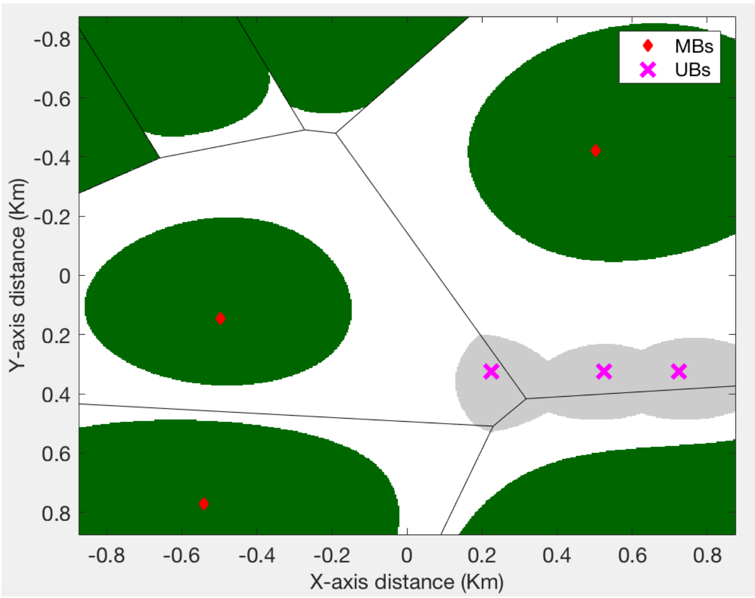

Figure 4.6: Image of the throughput coverage after a hurricane and 3 UABSs are being deployed at the height of 243.83 meters or 800 feet

4.4.3 The height of UAVs at 487.68 meters (1200 feet)

Furthermore, when you continue to increase the height of the UAVs in our case from 243.84 meters (800 feet) to 487.68 meters (1200 feet) as shown in the table 4.4 below. The throughput coverage is way out of range and unseen, as indicated by the pink cross in the graph below in figure 4.7.

Table 4.4: System parameters for the use of 3 UAVs at a height of 1200 feet

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	4
Height of UABs	487.68 meters or (1200 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	3
PercDestroyMBs	70%

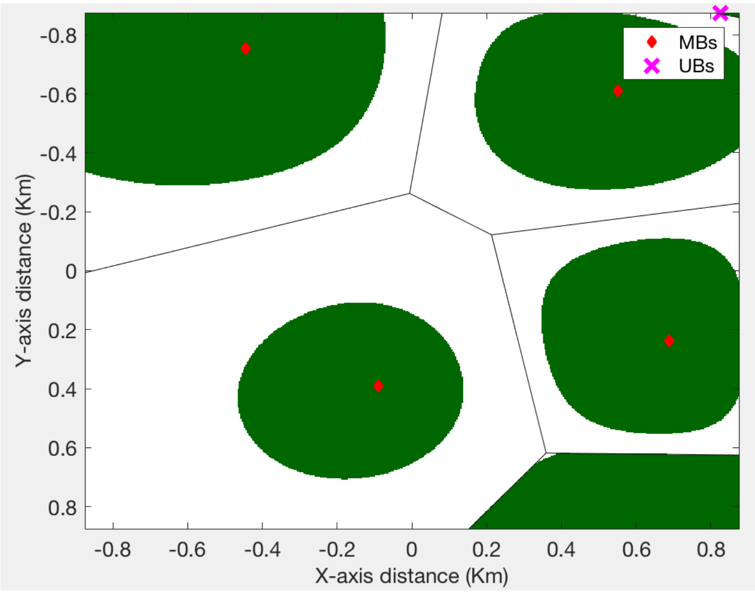

Figure 4.7: Image of the throughput coverage after an hurricane and 3 UABSs are deployed at the height of 487.68 meters or 1200 feet

In our findings, the simulation results prove that when you increase the height of the UAV, this does not always mean better coverage as in our case. We assumed that due to the distance of the UAV to the UE, this would create a lack of throughput coverage.

4.5 Investigating the number of UAVs deployed

The following set of parameters as shown in table 4.5 below considers an increase in the number of UAVs deployed from 3 UAVs in the above set of simulation results to 6 UAVs. Furthermore, while we set the number of UAVs to 6, we also applied the heights of the UAVs at 121.92 meters as in figure 4.5, 243.84 meters as in figure 4.6 and 487.68 meters as in figure 4.7 while all other parameter value remains the same.

4.5.1 6 UAVs at 121.92 meters (400 feet) in height

Table 4.5: System parameters for the use of 6 UAVs at a height of 400 feet

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	4
Height of UABs	121.92 meters or (400 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	6
PercDestroyMBs	70%

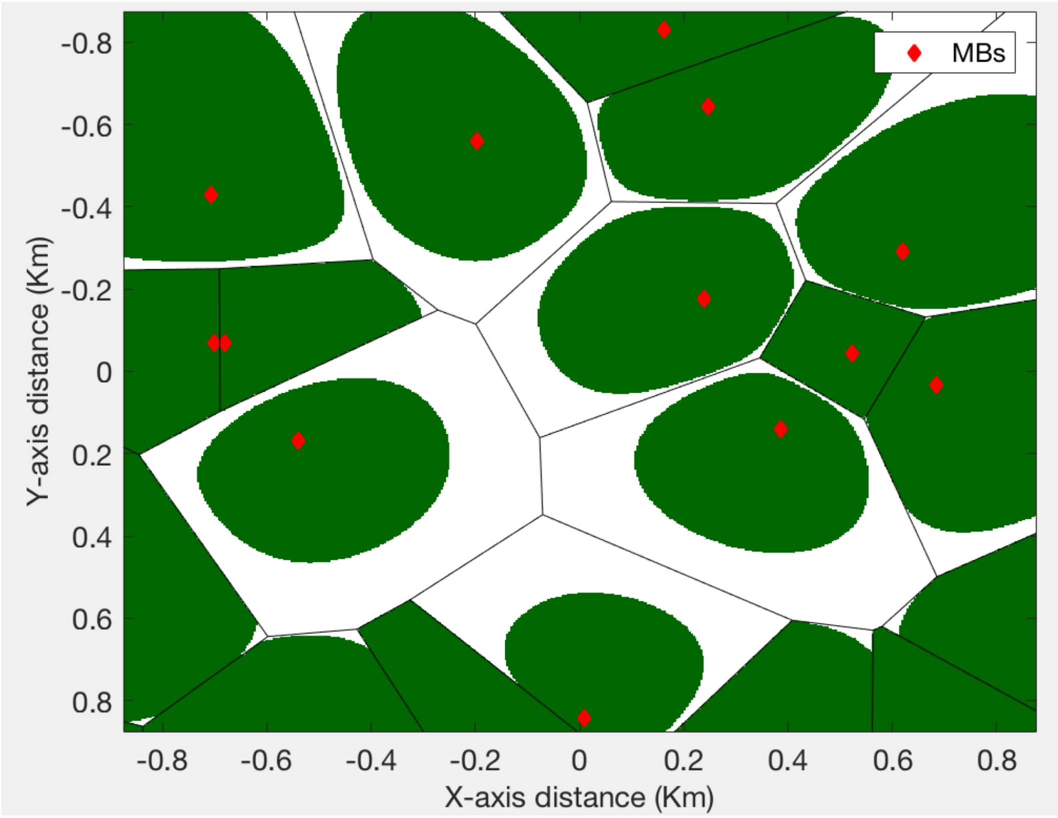

Figure 4.8: The image of the throughput coverage before a hurricane when the testing process is based on the number of UAVs deployed

The above figure 4.8 shows the communication network before any natural disaster happens where the macro base station used only and depicted by the red pointer on the graph. The green area is the throughput coverage.

In figure 4.9 below, the throughput coverage area has been reduced dramatically, caused by a severe hurricane. The graph also shows the simulation results when the parameters are set to values as in table 4.5 above. At this stage, there is 70% of the MBs destroyed during a natural disaster.

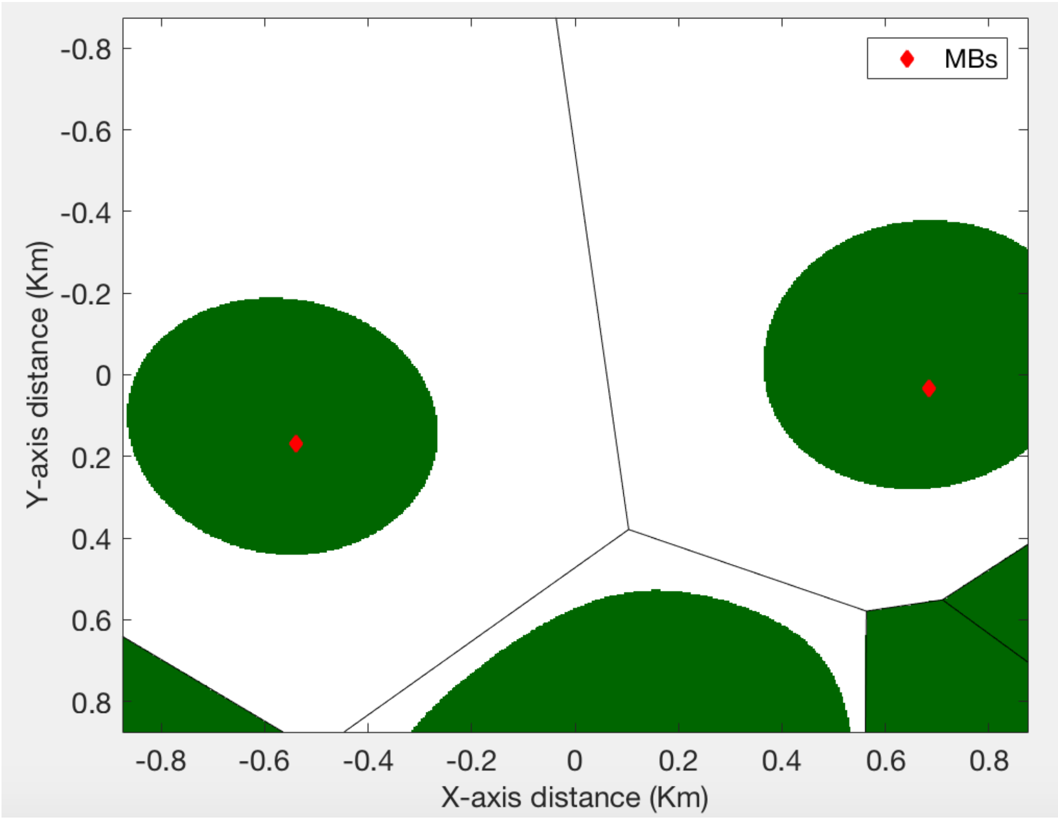

Figure 4.9: Image of the throughput coverage after an hurricane and 70% of MBs are destroyed. The focus of the test in on the number of UAVs deployed

Furthermore, figure 4.10 below shows 6 UABS deployed as indicated by the pink crosses on the graph. The grey area is the new throughput coverage created by positioning the UAVs at optimized locations using brute force search.

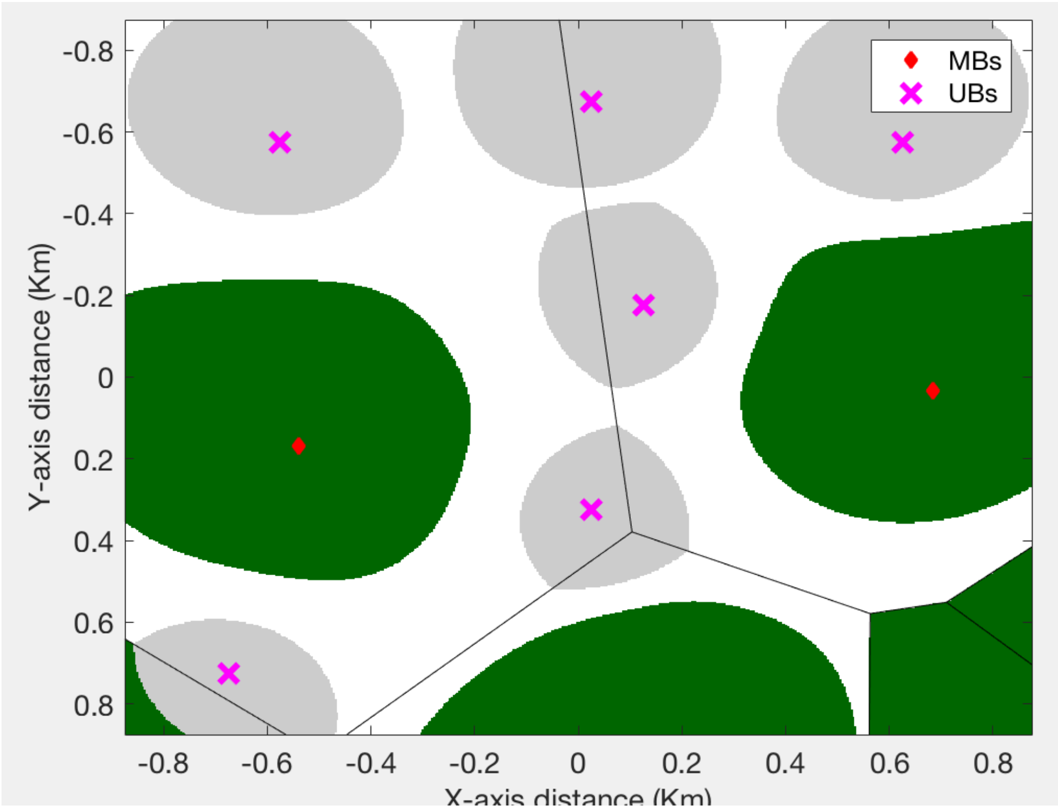

Figure 4.10: Image of the throughput coverage after a hurricane and when 6 UAVs are being deployed at the height of 121.92 meters or 400 feet

4.5.2 6 UAVs at 243.84 meters (800 feet) in height

At the height of 243.84 meters (800 feet), the following table 4.6 below shows the value of parameters still remaining the same at default except for the number of UAVs at 6 and the height changed.

Table 4.6: System parameters for the use of 6 UAVs at a height of 800 feet

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	4
Height of UABs	243.84 meters or (800 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	6
PercDestroyMBs	70%

The figure 4.11 below shows the current macro base stations (MBs) at their locations in the chosen area before the effect of a natural disaster. The throughput coverage covers a large area within the chosen area as shown by the green colored spots on the graph.

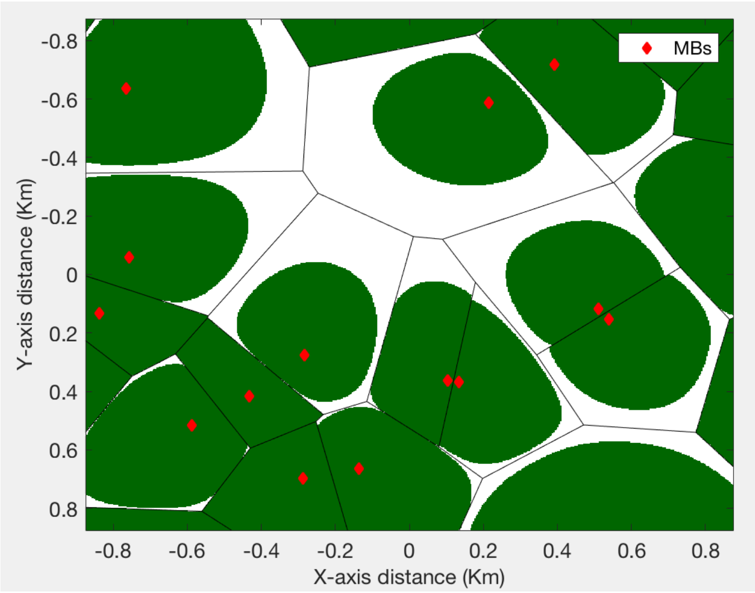

Figure 4.11: The image of the throughput coverage before a hurricane. Parameter settings as that in table 4.6 above

The test results of the simulation as shown below in figure 4.12 illustrates what happens after a natural disaster, 70% of the existing macro base stations are destroyed, and the rest of the parameters are set at the value in table 4.6 above.

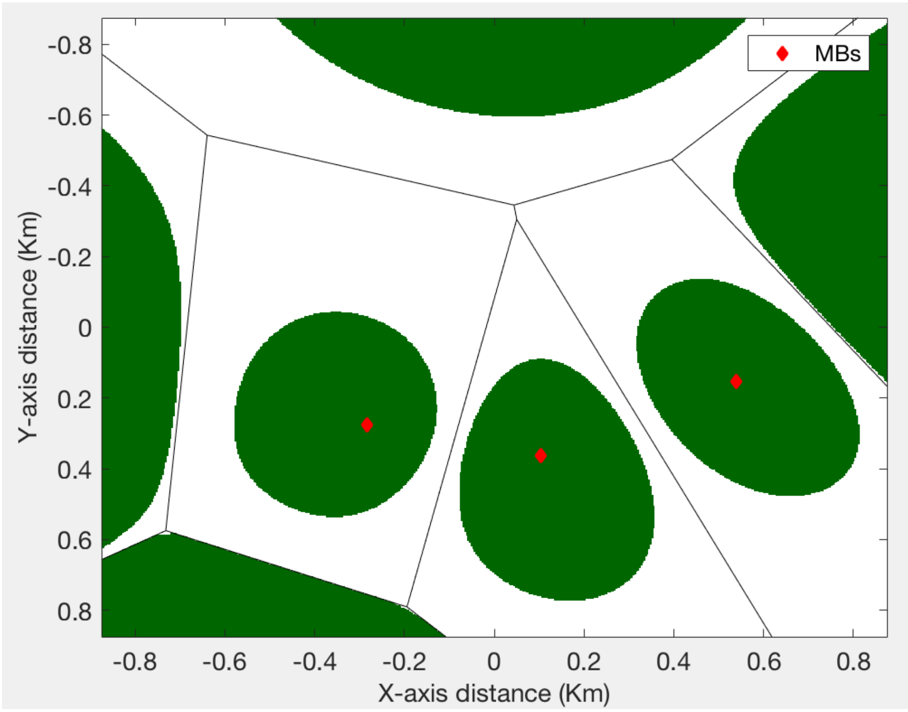

Figure 4.12: Image of the throughput coverage after a hurricane and 70% of MBs are destroyed. The parameter settings are in table 4.6 above

Setting the parameters value in table 4.6 above, we can see the impact of deploying 6 UABS on the throughput coverage. However the increase in height for the 6 UABS does not make much difference to the throughput coverage, as indicated by the grey area shown in the graph.

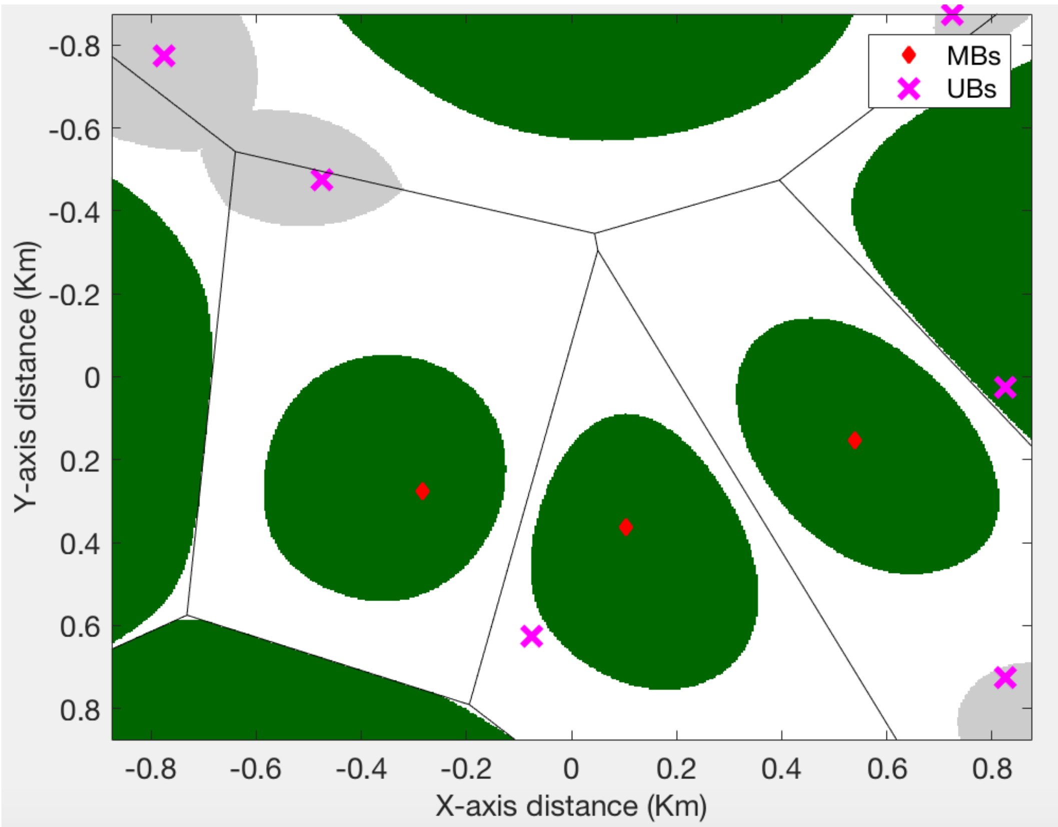

Figure 4.13: Image of the throughput coverage after an hurricane and 6 UABSs are being deployed at the height of 243.84 meters or 800 feet

4.6 Investigating the path loss exponent (PLE)

The following set of tables of parameter settings and figures that follow illustrates the changes in path loss exponent (PLE) while all other factors remain the same in value [89].

Table 4.7: Different physical lossy environments vs. PLE δ

Environment	Path loss exponent
In-door	1.6 to 1.8
Free space	2
Urban area	2.7 to 3.5
SubUrban area	3 to 5

4.6.1 PLE set to 5 with 3 UAVs deployed

For example, the table 4.8 below has shown an increase in the number of PLE from 4 to 5 and 3 UAVs deployed at the height of 121.92 meters (400 feet).

Table 4.8: System parameters for the use of 3 UAVs at a height of 400 feet and PLE set to 5

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	5
Height of UABs	121.92 meters or (400 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	3
PercDestroyMBs	70%

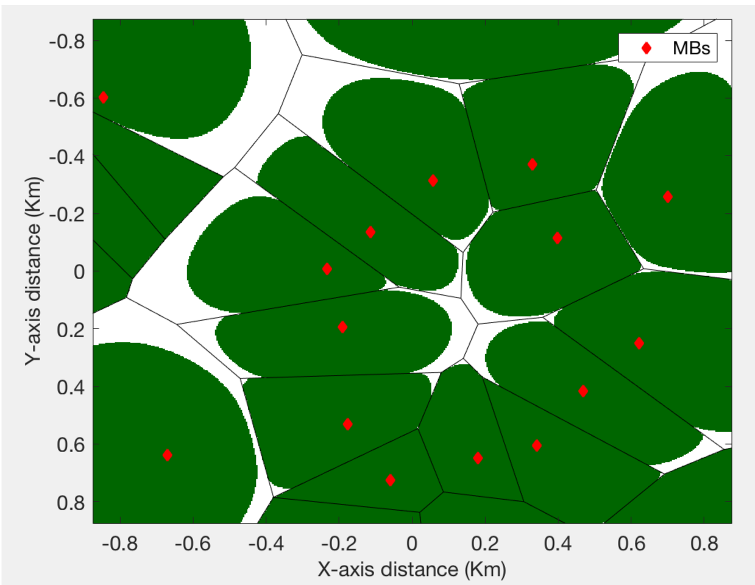

Figure 4.14: The image of the throughput coverage area before a hurricane. The testing process focuses on the path loss exponent PLE. Parameter settings are in table 4.8 above

The figure 4.14 above is the simulation results when the parameters are set to the values as that in table 4.8 above. The throughput coverage as shown in the graph by the green colored spots are produced by the MBSs. Prior to any natural disaster, all available macro base stations are currently functioning hence the large throughput coverage.

In the next graph, we examined the level of destruction caused by a category 4 or 5 hurricane. When all other values remain the same to the set of parameters as shown in table 4.8 and 70% of the macro base stations are destroyed after a natural disaster. Figure 4.15 below shows the networking system with poor throughput coverage as some of the macro base stations are no longer functioning.

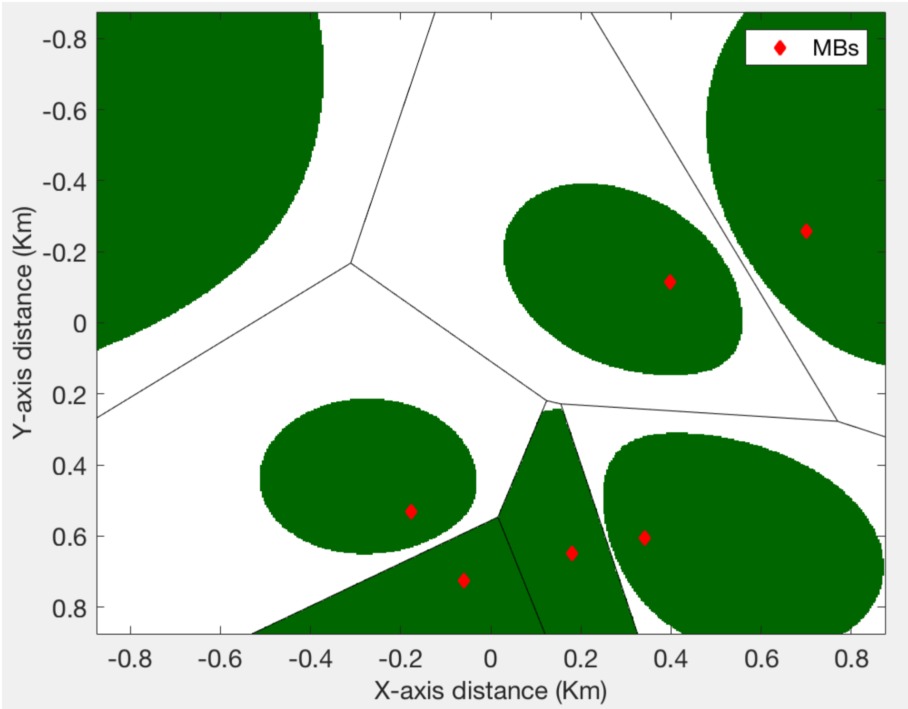

Figure 4.15: Image of the throughput coverage after a hurricane and 70% of MBs are destroyed. The parameter settings are in table 4.8 above

When deploying 3 UAVs and the changes made to the PLE at 5, figure 4.16 below indicates the level of throughput coverage by the grey area. In reality, the alternative aerial communication is required by first responders to initiate their search and rescue mission. By creating a new area of throughput coverage via UABSs, emergency respond teams will use this coverage area to communicate with victims and monitor the affected areas.

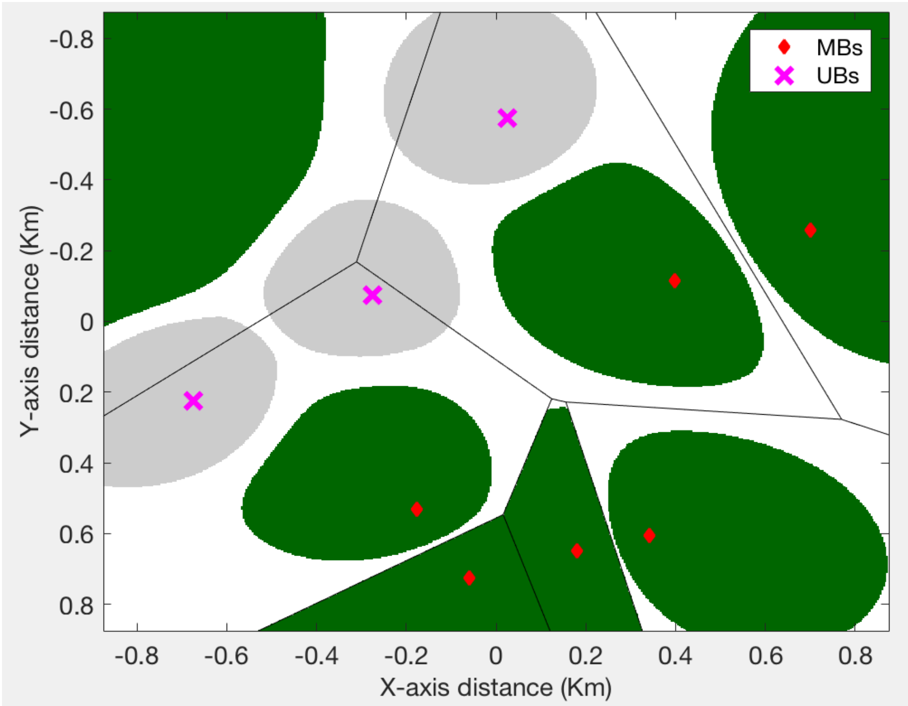

Figure 4.16: Image of the throughput coverage after a hurricane and 3 UABSs are being deployed with the path loss exponent PLE set at 5

4.6.2 PLE set to 6 and 3 UAVs deployed

The following set of tables and figures represent a senario where we take into consideration the path loss exponent. In this case, we have increased the PLE to 6 and all other parameter values remain the same as in table 4.9 below.

Table 4.9: System parameters for the use of 3 UAVs at a height of 400 feet and PLE set to 6

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	6
Height of UABs	121.92 meters or (400 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	3
PercDestroyMBs	70%

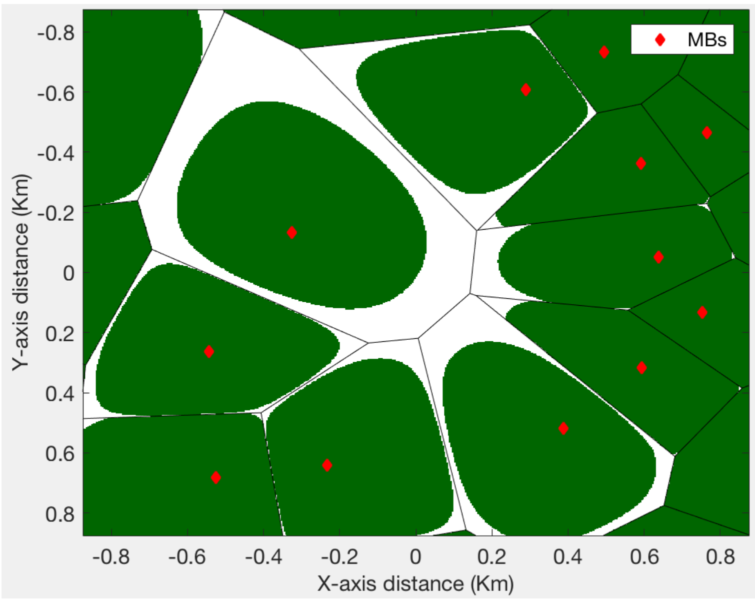

Figure 4.17: Image of the throughput coverage before a hurricane. Parameter settings are in table 4.9 above

After a natural disaster strikes and 70% of the macro base stations are destroyed. The following figure 4.18 shows the impact of the destruction causing low throughput coverage.

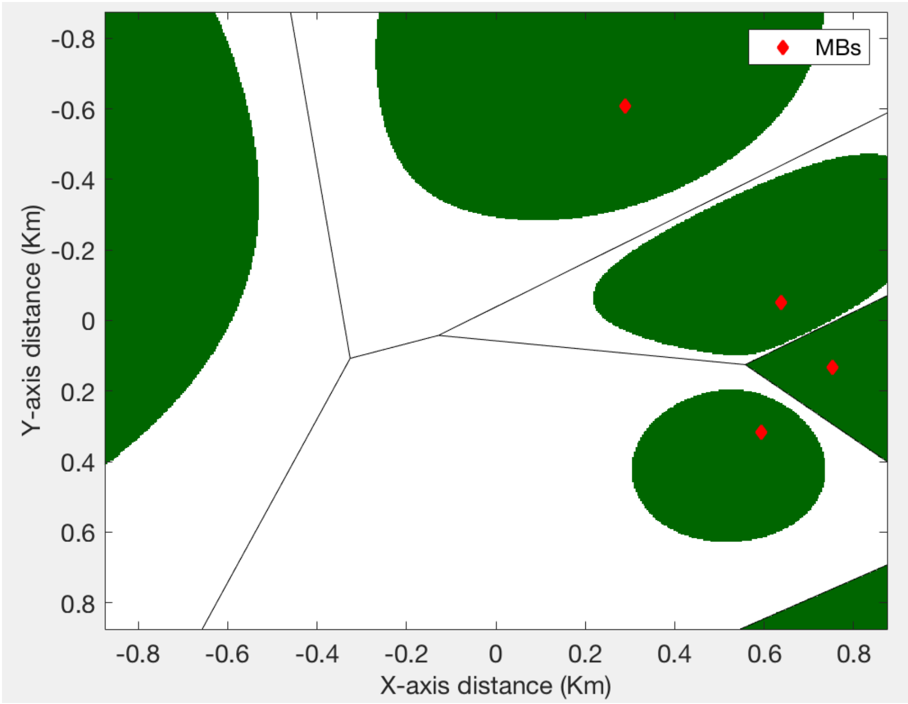

Figure 4.18: Image of the throughput coverage after a hurricane and 70% of MBs are destroyed. The parameter settings are in table 4.9 above

When deploying 3 UAVs at the height of 121.92 meters (400 feet) and the path loss exponent (PLE) is 6, the figure 4.19 below provides the simulation results. There is a new throughput coverage as indicated by the grey area.

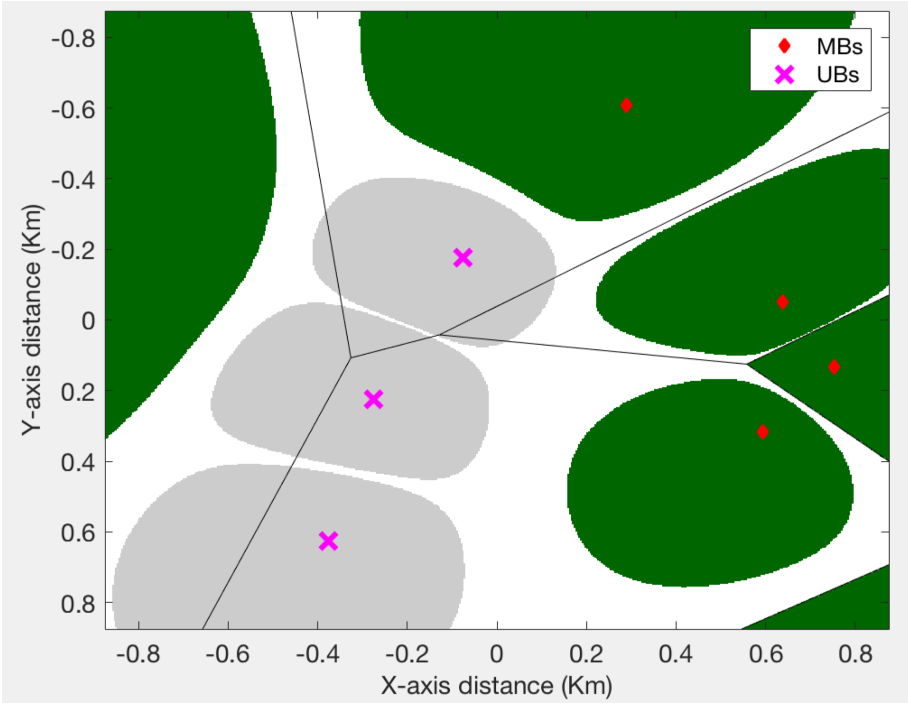

Figure 4.19: Image of the throughput coverage after a hurricane and 3 UABSs are being deployed and the path loss exponent PLE is set at 6

4.6.3 PLE set to 6 and 6 UAVs deployed

In the following table 4.10 of parameter settings, we have changed the number of UAVs from 3 to 6 and the path loss exponent (PLE) from 5 to 6. Figure 4.20, 4.21 and 4.22 below is the simulation results showing the current communication system before a natural disaster, after a natural disaster and 70% of the MBSs are destroyed, and the new throughput coverage after deploying 6 UAVs respectively.

Table 4.10: System parameters for the use of 6 UAVs at a height of 400 feet and PLE set to 6

The simulation parameters.	
Parameter	***Value***
MBs and UE intensities	4 and 800 per km^2
MBs and UABs transmission powers	46dBm and 30dBm
Path-loss exponent (PLE)	6
Height of UABs	121.92 meters or (400 feet)
Simulation area	2.5*2.5 km ^2
NoUABs used	6
PercDestroyMBs	70%

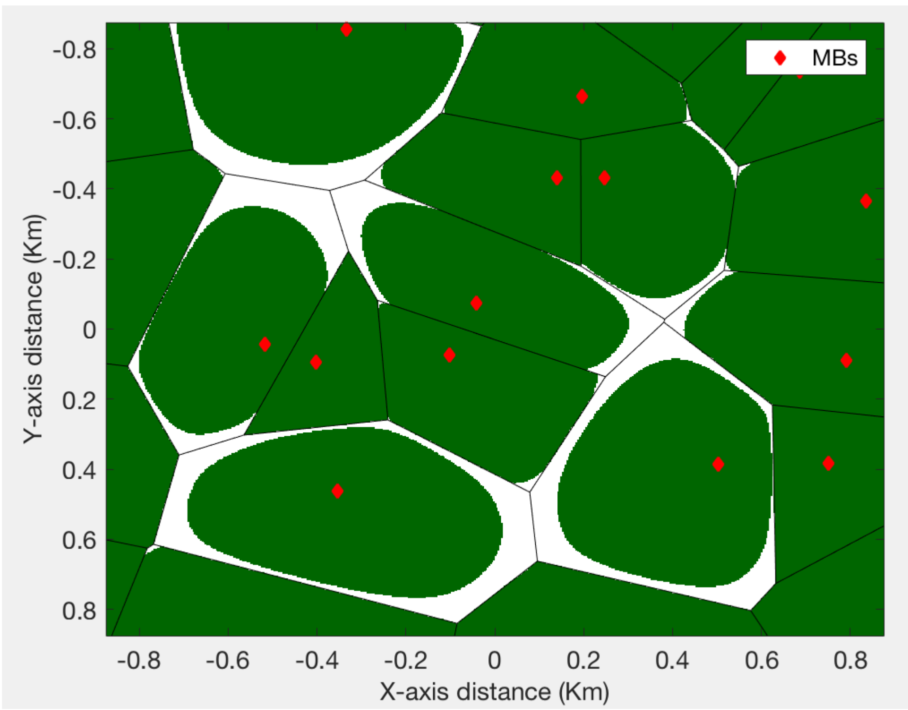

Figure 4.20: Illustrate the network layout before a natural disaster

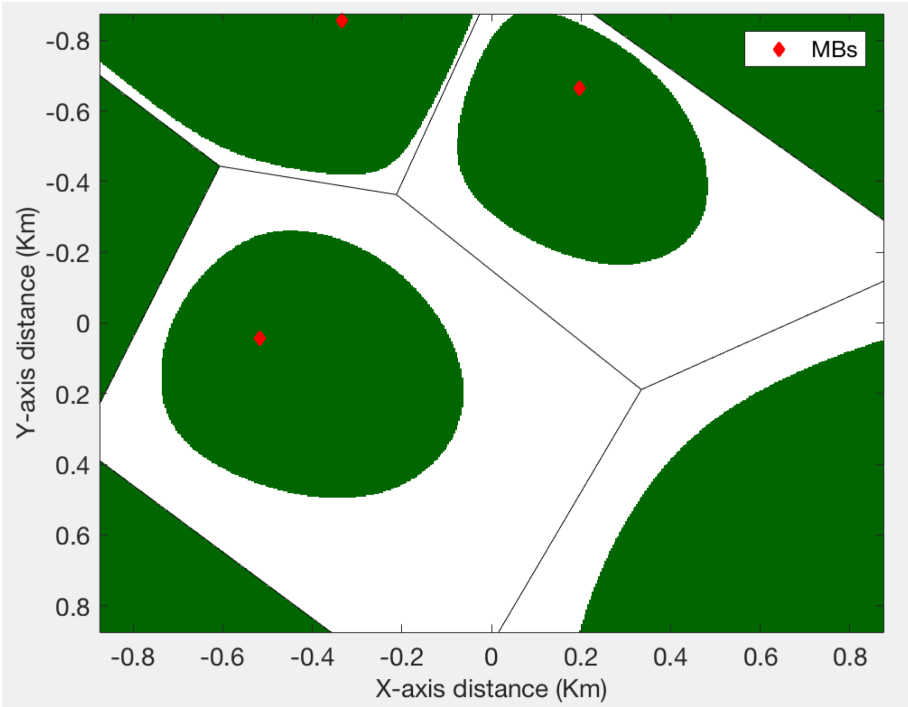

Figure 4.21: Illustration of throughput coverage after a natural disaster when 70% of MBs is destroyed

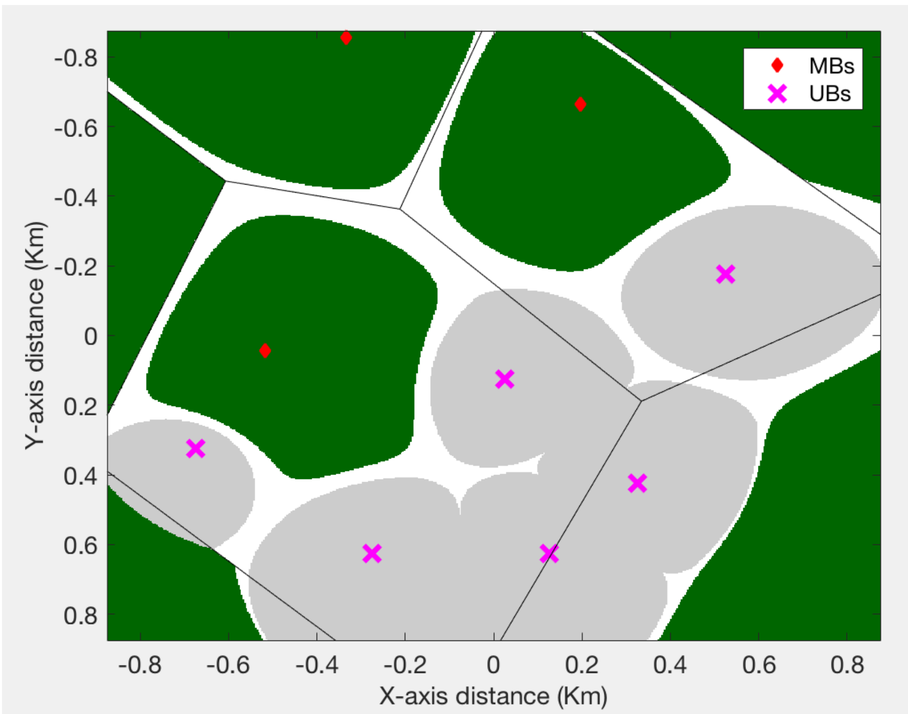

Figure 4.22: Illustration of throughput coverage when 6 UBs are used

The result of the simulation shows that when you increase the number of PLE together with the number of UAVs deployed, you are likely to increase the throughput coverage over the area network as compared to an increase in the height of the UAVs together with the number of UAVs deployed where the throughput coverage decreases.

4.7 Investigating the 5th Percentile

As mentioned earlier, we used brute force search for simplicity to position the UAVs at optimized location and to maximize the 5th percentile spectral efficiency (SE) of the network.

In figure 4.23 and figure 4.24 below, we showed the deployment of 3 and 6 UAVs. The X-axis in both figures is the path loss exponent (PLE) and the Y-axis in figure 4.23 is the 5th percentile and in figure 4.24 is the network coverage. The N_{dst} represents the number of macro base stations (MBSs) destroyed out of a total of 400.

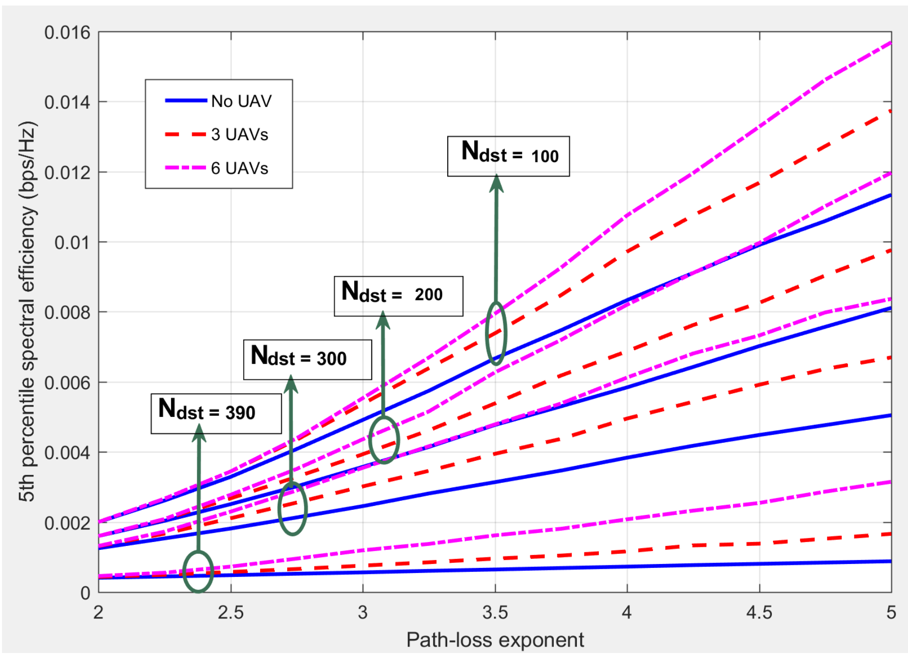

Figure 4.23: Effects of PLE on the 5th percentile (SE)

The results of the experiment show that an increase in PLE also increases the throughput coverage. When the number of UAVs that are being deployed increases from 3 to 6, the results show a maximum gain. In general, the 5th percentile SE and the throughput coverage improves when the PLE is increased.

In the figure 4.24 below, we can see that the throughput coverage improves dramatically as the number of UAVs increases and the PLE is higher. For example, in our case where 390 out of the 400 MBSs are destroyed, about 90% of the affected area can still be covered when 6 UABSs are being deployed and given that the PLE is set at 4.

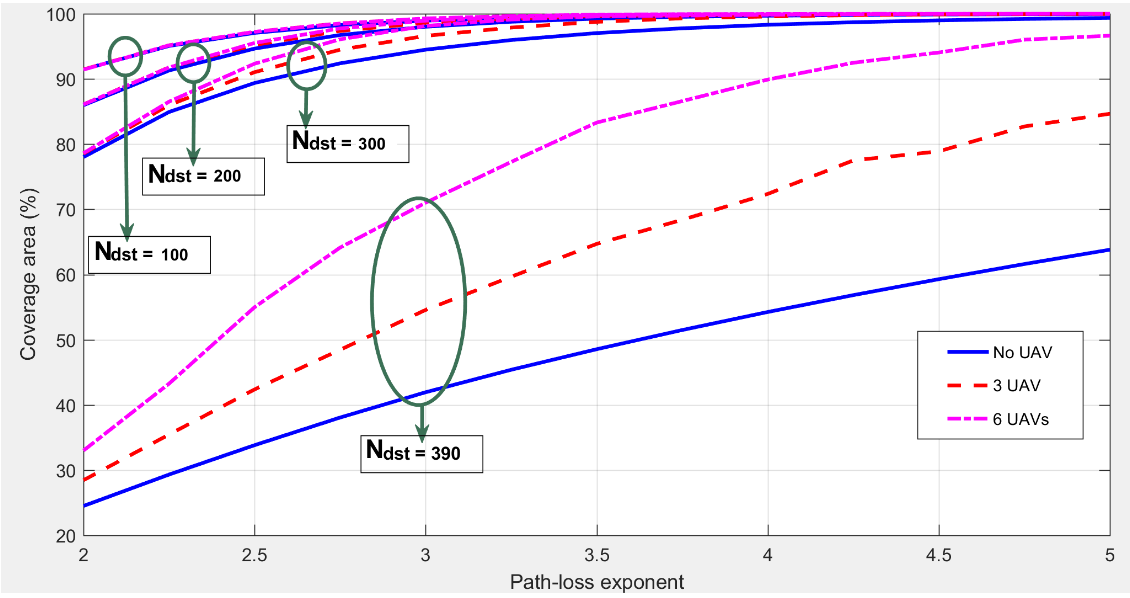

Figure 4.24: Effects of PLE on throughput coverage area

In our case, when we test the 5th percentile, we can say that the interference power at the UE will decrease at a faster speed compared to the signal power as the PLE increases causing the SIR to improve from the UE viewpoint. The decrease in the interference power at the UE is due to the distance of the UEs from its serving MBS, it is also less than all other interfering MBSs.

4.8 Summary

As previously mentioned, the focus of conducting the simulation is to find the optimized location for UABS to improve throughput coverage in an area affected by a natural disaster. While others used genetic algorithm, we used brute force search for simplicity to randomly distribute and locate the UABSs. In the testing process, we focused our attention on four main parameter settings which include the heights of the UAVs or UABS in which it has to be deployed. We also focused on the impact of throughput coverage when we changed the number of UAVs deployed and also tested what happened to the level of coverage if we changed the path loss exponent (PLE) as well as the 5th percentile.

The results of the simulation provide the following conclusions which indicates that when we first tested for the height of the UAVs when deployed and keeping the rest of the other parameter setting at default values, the results proved that when you increase the height of the UAV, it did not improve the coverage. We assumed that this has to do with the distance of UAV to the UE that created the lack of throughput coverage.

Furthermore, the results of the simulation show that when you increase the number of PLE together with the number of UAVs deployed, you are likely to increase the throughput coverage over the area network as compared to an increase in the heights of the UAVs together with the number of UAVs deployed where the throughput coverage decreases. Lastly, in general, the 5th percentile SE and the throughput coverage improves when the PLE is increased.

Chapter 5

Conclusion and Future Work

5.1 Introduction

In this century as technology advances, more people are relying on the cutting edge technology available to them. The use of UAVs is one of the promising new technologies that now provide potentials in many areas of life. Some of the useful purposes of UAVs, include its use in the areas of military, telecommunications, agriculture, health, tourism for filming, search and rescue, infrastructure, surveillance, gaming and journalism among many others.

Furthermore, we considered the case where a UAV is used to form part of a communication infrastructure that has been severely paralyzed and affected by a natural disaster. Our case study is based around the use of UAVs to aid in a disaster management plan to be used when required on the island of Rarotonga in the Cook Islands.

There is no doubt about the potential benefits that UAVs bring to society. As indicated in the literature, even major names such as Google and Facebook are moving further utilizing UAVs to perform jobs that man may not be able to do. Most importantly, UAVs are now performing tasks that are considered dangerous to man and saving man's life in return.

As this research focuses on the use of UAVs as part of a telecommunication system, we further examined other underlying topics such as the traditional networking system versus the more advanced LTE networking system. We found that the former provides voice communication only while the latter is capable of producing voice, video and data which is preferred by emergency response personnel during a natural disaster situation. The reliable and cost efficient HetNet communication system is also discussed. This form of networking system is the solution to a situation where part of the traditional networking system has been destroyed in a natural disaster. UAVs are deployed in the air as UABSs along with the remaining macro base stations to maintain communication channels.

Furthermore, we looked into the topic of UAV networking topology where we found that there is a mesh and a star form of topology. In our case study, we considered a mesh topology due to its flexibility and reliability features. We also considered the multi-UAV system to be the best to use over a single UAV system. Having to deploy and use multiple UAVs as part of our HetNet, eliminates the cost of total shut down as the communication channel survives through a redundancy system, while the single UAV system lacks this important point. In addition, we also looked at the different types of handovers and chose the soft over the hard handover as the former does not allow any interferences in communication by the UE.

5.2 Answering our research questions

5.2.1 Primary research question

Question - How to effectively use UAVs to optimize communication coverage in the aftermath of a natural disaster?

Answer - We used brute force search for simplicity to randomly place UAVs at optimized locations and also focused our simulation experiment on specific parameter settings. These include the heights of the UAVs when deployed, the number of UAVs to be deployed, looking at the path loss exponent (PLE) as well as the 5th percentile.

Using brute force search is based on trial and error and although the process may be long, the results of the simulation provide promising conclusions.

5.2.2 Research sub-questions

Question - How can we improve the quality of communication required by emergency first responders in the event of a natural disaster?

Answer - Based on our research and focusing our response to suit our case study, we can say that by introducing the latest LTE technology to replace the traditional networking system currently used on the island is a great start. Emergency first responders will not only be able to have voice communication but also video and data available to them. The live streaming of messages and video surveillance during a natural disaster will provide faster services by emergency first responders as they are able to monitor the affected area, make safety and rescue plans, and continue to communicate in and out of the affected area.

Question - How to maximize the performance of UAVs used as UABS in the event of a natural disaster?

Question - Why do we use multiple UAVs rather than one UAV as base stations and what are the advantages and disadvantages in applying this method?

Answer – According to our research, we know that UAVs are designed differently and according to its missions or required purpose. In our case, we are looking at a specific task oriented purpose for UAVs that will form part of an HetNet system. In a mixed advanced networking system where both macro and micro base stations are used to provide aerial channels of communication, it is important that UAVs are designed to cater for a hostile and critical form of environment. Therefore, we decided to use a UAV equipped with video and voice recording technology as well as aerial antennas capable of providing broadband data for communication. In order to maximize the performance of UAVs in terms of battery life, we considered using green energy as this is cost efficient and effective. We also looked at deploying multiple UAVs rather than a single UAV as UABS in this situation. Deploying multiple UAVs provides a safer alternative in terms of redundancy being achieved rather than a total breakdown due to a single UAV without backups.

Question - At what level of performance would you consider safe coverage is achieved?

Answer - In this work, one major goal to be considered is the ability to achieve an exceptional broadband rate in an area where there is poor or no coverage at all. In order to find this out, we use the throughput coverage as the performance indicator for network coverage. The 5th percentile is a fitness function that represents the throughput coverage of the whole network in this case study therefore our aim is to see that the 5th percentile rate is increased to know that safe coverage is achieved. Generally speaking, when all UE experience good level of communication, where no interference to communication is realized, then we can also say that safe coverage has been achieved.

Question - How much will it cost to use UAVs as UABS in temporary situations such as in the event of a natural disaster?

Answer – UAVs are relatively cheaper compared to other platforms such as aircrafts or spaceships because of their sizes. Drones or UAVs are highly dynamic in nature and are easy to deploy and have softer regulations compared to other bigger aircrafts. In most projects, the initial costs are normally the bulk amount of costing and in our case, the cost relating to the components of the UAVs is the main cost. Deploying the technology is relatively easy and the cost will be low, however those responsible for the project should be well skilled and trained on various aspect of this new form of technology.

5.3 Summary of the simulation results

Our simulation results show that, in the event of a natural disaster and part of the networking infrastructure has been destroyed, the deployment of UABSs at optimized locations can improve the throughput coverage. In addition to this process, when changing the heights of UABSs alone does not always mean better coverage however we have to consider other areas such as the number of UABSs to deploy as well as the path loss exponent and the 5th percentile.

To conclude the simulation results, we found that when you increase the number of PLE together with the number of UAVs deployed, you are likely to increase the throughput coverage over the area network. When compared to an increase in the height of the UAVs together with the number of UAVs deployed, the throughput coverage decreases. Lastly, the 5th percentile SE and the throughput coverage improves when the PLE is increased.

5.4 Conclusion

An effective communication infrastructure is extremely important in providing safety and emergency information to the general public, for first responders to coordinate rescue and recovery plans, and civilian needs to communicate with emergency first responders. The research conducted provides information on the latest advanced technology. UAVs are used as UABSs to provide temporary solutions to communication coverage in situations where part of an existing communication infrastructure is damaged and not functioning due to a natural disaster. By using a simulation, we are able to examine the throughput coverage achieved by utilizing the mobility features of UAVs. The results of the simulation show that when using UABS in a dysfunctional communication system, it can improve the throughput coverage and the spectral efficiency of the communication network when the UABSs are placed at optimized locations.

5.5 Future works

For future works, we can look at other challenging networking approaches such as Delay Tolerant Network (DTN) which is another type of routing protocol that works by storing and carrying data for end users and is useful in critical disaster situations as discussed by the authors of [90] and [91, 92].

Another challenging network that we can further look at is the efficient 3-D placement algorithm. The 3-D placement of drone-cell considers jointly together the location or placement and the altitude of drone-cell rather than a 1-D that considers the altitude only. The 2-D only reflects the placement of drone-cell in the horizontal space [11].

References

[1] A. S. GIBB, "Droning the story," Ph.D. dissertation, UNIVERSITY OF BRITISH COLUMBIA (Vancouver, 2013.

[2] S. Fu and Y. Wan, "Communicating in remote areas or disaster situations using unmanned aerial vehicles," *links*, vol. 6, p. 7.

[3] N. I. of Standards and T. E. Laboratory., "Community resilience workshops." [Online]. Available: http://www.nist.gov/el/resilience/disre-sworkshp.cfm

[4] A. C. Weaver, G. Byrd, and R. Bryce, "Computing tools and techniques for emergency response," *Computer*, vol. 49, no. 5, pp. 16–18, 2016.

[5] M. Erdelj and E. Natalizio, "Uav-assisted disaster management: Applications and open issues," in *2016 International Conference on Computing, Networking and Communications (ICNC)*. IEEE, 2016, pp. 1–5.

[6] Y. Bai, W. Du, Z. Ma, C. Shen, Y. Zhou, and B. Chen, "Emergency communication system by heterogeneous wireless networking," in *Wireless Communications, Networking and Information Security (WCNIS), 2010 IEEE International Conference on*. IEEE, 2010, pp. 488–492.

[7] G. Bartoli, R. Fantacci, F. Gei, D. Marabissi, and L. Micciullo, "A novel emergency management platform for smart public safety," *International Journal of Communication Systems*, vol. 28, no. 5, pp. 928–943, 2015.

[8] E. Ackerman, "Drone adventures uses uavs to help make the world a better place," *IEEE Spectrum*, 2013.

[9] A. Thakur and C. Hota, "Sustainable wireless internet connectivity for rural areas," in *Advances in Computing, Communications and Informatics (ICACCI), 2013 International Conference on*. IEEE, 2013, pp. 1335–1340.

[10] I. Bor-Yaliniz and H. Yanikomeroglu, "The new frontier in ran heterogeneity: Multi-tier drone-cells," *arXiv preprint arXiv:1604.00381*, 2016.

[11] R. Yaliniz, A. El-Keyi, and H. Yanikomeroglu, "Efficient 3-d placement of an aerial base station in next generation cellular networks," *arXiv preprint arXiv:1603.00300*, 2016.

[12] C. I. T. Corporation., "Cook islands." [Online]. Available: https://www.cookislands.travel/contact-us

[13] J. Roberts., "The cook islands south pacific." [Online]. Available: http://www.cookislands.org.uk/

[14] A. Merwaday and I. Guvenc, "Uav assisted heterogeneous networks for public safety communications," in *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*. IEEE, 2015, pp. 329–334.

[15] S. Round, "Resilience amid the struggle - one year on from cyclone winston." [Online]. Available: http://www.radionz.co.nz/international/pacific-news/324871/resilience-amid-the-struggle-one-year-on-from-cyclone-winston

[16] A. Merwaday, A. Tuncer, A. Kumbhar, and I. Guvenc, "Improved throughput coverage in natural disasters: Unmanned aerial base stations for public-safety communications," *IEEE Vehicular Technology Magazine*, vol. 11, no. 4, pp. 53–60, 2016.

[17] L. Chiaraviglio, N. Blefari-Melazzi, W. Liu, J. A. Gutierrez, J. Van De Beek, R. Birke, L. Chen, F. Idzikowski, D. Kilper, P. Monti *et al.*, "5g in rural and low-income areas: Are we ready?" in *The 8th ITU Kaleidoscope academic conference*, 2016.

[18] O. Onireti, M. A. Imran, J. Qadir, and A. Sathiaseelan, "Will 5g see its blind side? evolving 5g for universal internet access," *arXiv preprint arXiv:1603.09537*, 2016.

[19] M. Yuksel, I. Guvenc, W. Saad, and N. Kapucu, "Pervasive spectrum sharing for public safety communications," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 22–29, 2016.

[20] G. Baldini, S. Karanasios, D. Allen, and F. Vergari, "Survey of wireless communication technologies for public safety," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 619–641, 2014.

[21] H. Eisenbeiß, *UAV photogrammetry*. ETH Zurich, Switzerland:, 2009.

[22] M. Gharibi, R. Boutaba, and S. L. Waslander, "Internet of drones," *IEEE Access*, vol. 4, pp. 1148–1162, 2016.

[23] L. Krock, "Time line of uavs." [Online]. Available: http://www.pbs.org/wgbh/nova/spiesfly/uavs.html

[24] Micrdrone, "History of drones." [Online]. Available: http://www.pbs.org/wgbh/nova/spiesfly/uavs.html

[25] M. Arjomandi, S. Agostino, M. Mammone, M. Nelson, and T. Zhou, "Classification of unmanned aerial vehicles," *Report for Mechanical Engineering class, University of Adelaide, Adelaide, Australia*, 2006.

[26] S. Chandrasekharan, K. Gomez, A. Al-Hourani, S. Kandeepan, T. Rasheed, L. Goratti, L. Reynaud, D. Grace, I. Bucaille, T. Wirth *et al.*, "Designing and implementing future aerial communication networks," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 26–34, 2016.

[27] I. Bucaille, S. Hethuin, T. Rasheed, A. Munari, R. Hermenier, and S. Allsopp, "Rapidly deployable network for tactical applications: Aerial base station with opportunistic links for unattended and temporary events absolute example," in *Military Communications Conference, MILCOM 2013-2013 IEEE*. IEEE, 2013, pp. 1116–1120.

[28] C.-J. Ahn, "Wireless power transmission with rough beamforming method," in *Information and Computer Science (NICS), 2015 2nd National Foundation for Science and Technology Development Conference on*. IEEE, 2015, pp. 305–309.

[29] A. Sathiaseelan, A. Lertsinsrubtavee, P. Baskaran, J. Crowcroft *et al.*, "Cloudrone: Micro clouds in the sky," *arXiv preprint arXiv:1604.08243*, 2016.

[30] I. Bekmezci, O. K. Sahingoz, and Ş. Temel, "Flying ad-hoc networks (fanets): A survey," *Ad Hoc Networks*, vol. 11, no. 3, pp. 1254–1270, 2013.

[31] A. Ryan and J. K. Hedrick, "A mode-switching path planner for uav-assisted search and rescue," in *Decision and Control, 2005 and 2005 European Control Conference. CDC-ECC'05. 44th IEEE Conference on*. IEEE, 2005, pp. 1471–1476.

[32] S. Waharte and N. Trigoni, "Supporting search and rescue operations with uavs," in *Emerging Security Technologies (EST), 2010 International Conference on*. IEEE, 2010, pp. 142–147.

[33] Micrdrone, "Search and rescue with uavs." [Online]. Available: https://www.microdrones.com/en/applications/areas-of-application/search-and-rescue/

[34] A. Raptopoulos., "No roads? there's a drone for that." [Online]. Available: https://www.ted.com/talks/andreas_raptopoulos_no_roads_there_s_a_drone_for_that

[35] D. Gross, "Amazon's drone delivery: How would it work?" *CNN. Cable News Network*, vol. 2, 2013.

[36] Amazon, "Amazon prime air." [Online]. Available: https://www.amazon.com/b?node=8037720011

[37] R. D'Andrea, "Guest editorial can drones deliver?" *IEEE Transactions on Automation Science and Engineering*, vol. 11, no. 3, pp. 647–648, 2014.

[38] A. Raptopoulos, "No roads? there is a drone for that." [Online]. Available: https://www.ted.com/talks/andreasraptopoulosnoroadstheresadroneforthat

[39] J. S. E. A. Mickey Foster, Stephen Hughes, “Q1 fiscal 2015 statistics.” [Online]. Available: http://investors.fedex.com/files/docdownloads/statistical/FedEx-Q1-FY15-Stat-Bookv001t195uu.pdf

[40] D. Gross, “Amazon’s drone delivery: How would it work?” [Online]. Available: http://www.cnn.com/2013/12/02/tech/innovation/amazon-drones-questions/

[41] J. Stewart, “Google test drone deliveries in project wing trials.” [Online]. Available: http://www.bbc.com/news/technology-28964260

[42] D. Express, “Dhl parcelcopter launches initial operations for research purposes.” [Online]. Available: http://www.dhl.com/en/press/releases/releases_2014/group/dhl_parcelcopter_launches_initial_operations_for_research_purposes.html

[43] T. Diaz, “Lights, drone... action,” *IEEE Spectrum*, vol. 52, no. 7, pp. 36–41, 2015.

[44] E. Natalizio, R. Surace, V. Loscri, F. Guerriero, and T. Melodia, “Filming sport events with mobile camera drones: Mathematical modeling and algorithms,” 2012.

[45] C. W. Bac, E. J. Henten, J. Hemming, and Y. Edan, “Harvesting robots for high-value crops: State-of-the-art review and challenges ahead,” *Journal of Field Robotics*, vol. 31, no. 6, pp. 888–911, 2014.

[46] G. Grenzdörffer, A. Engel, and B. Teichert, “The photogrammetric potential of low-cost uavs in forestry and agriculture,” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 31, no. B3, pp. 1207–1214, 2008.

[47] M. W. Davidson, T. Le Toan, F. Mattia, G. Satalino, T. Manninen, and M. Borgeaud, “On the characterization of agricultural soil roughness for radar remote sensing studies,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 38, no. 2, pp. 630–640, 2000.

[48] L. Nam, L. Huang, X. Li, and J. Xu, “An approach for coverage path planning for uavs,” in *Advanced Motion Control (AMC), 2016 IEEE 14th International Workshop on*. IEEE, 2016, pp. 411–416.

[49] L. Brief, “Growth opportunity in global uav market,” *Las Colinas, USA*, 2011.

[50] L. Gupta, R. Jain, and G. Vaszkun, “Survey of important issues in uav communication networks,” *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2015.

[51] A. Kedlaya, “Uav maritime surveillance,” Ph.D. dissertation, Manipal Institute of Technology, Manipal, 2014.

[52] E. Felemban, “Advanced border intrusion detection and surveillance using wireless sensor network technology,” *International Journal of Communications, Network and System Sciences*, vol. 6, no. 5, p. 251, 2013.

[53] E. Ackerman, "Japan earthquake: Global hawk uav may be able to peek inside damaged reactors," *IEEE Spectrum*, vol. 17, 2011.

[54] J. E. Triplett, "The effects of commercial video game playing: A comparison of skills and abilities for the predator uav," DTIC Document, Tech. Rep., 2008.

[55] D. Goldberg, M. Corcoran, and R. G. Picard, "Remotely piloted aircraft systems & journalism: opportunities and challenges of drones in news gathering," *Reuters Institute for the Study of Journalism. University of Ofxord*, 2013.

[56] A. Khandekar, N. Bhushan, J. Tingfang, and V. Vanghi, "Lte-advanced: Heterogeneous networks," in *Wireless Conference (EW), 2010 European*. IEEE, 2010, pp. 978–982.

[57] A. Kumbhar and I. Güvenç, "A comparative study of land mobile radio and lte-based public safety communications," in *SoutheastCon 2015*. IEEE, 2015, pp. 1–8.

[58] N. Nandiraju, D. Nandiraju, L. Santhanam, B. He, J. Wang, and D. P. Agrawal, "Wireless mesh networks: current challenges and future directions of web-in-the-sky," *IEEE Wireless Communications*, vol. 14, no. 4, pp. 79–89, 2007.

[59] S. Morgenthaler, T. Braun, Z. Zhao, T. Staub, and M. Anwander, "Uavnet: A mobile wireless mesh network using unmanned aerial vehicles," in *2012 IEEE Globecom Workshops*. IEEE, 2012, pp. 1603–1608.

[60] A. Jimenez-Pacheco, D. Bouhired, Y. Gasser, J.-C. Zufferey, D. Floreano, and B. Rimoldi, "Implementation of a wireless mesh network of ultra light mavs with dynamic routing," in *2012 IEEE Globecom Workshops*. IEEE, 2012, pp. 1591–1596.

[61] M. Ohleger, G. G. Xie, and J. H. Gibson, "Extending uav video dissemination via seamless handover: A proof of concept evaluation of the ieee 802.21 standard," in *System Sciences (HICSS), 2013 46th Hawaii International Conference on*. IEEE, 2013, pp. 5106–5114.

[62] J. Sen, "Mobility and handoff management in wireless networks," *arXiv preprint arXiv:1011.1956*, 2010.

[63] J. Schleich, A. Panchapakesan, G. Danoy, and P. Bouvry, "Uav fleet area coverage with network connectivity constraint," in *Proceedings of the 11th ACM international symposium on Mobility management and wireless access*. ACM, 2013, pp. 131–138.

[64] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *arXiv preprint arXiv:1602.03602*, 2016.

[65] R. I. Bor-Yaliniz, A. El-Keyi, and H. Yanikomeroglu, “Efficient 3-d placement of an aerial base station in next generation cellular networks,” in *Communications (ICC), 2016 IEEE International Conference on*. IEEE, 2016, pp. 1–5.

[66] O. K. Sahingoz, “Mobile networking with uavs: opportunities and challenges,” in *Unmanned Aircraft Systems (ICUAS), 2013 International Conference on*. IEEE, 2013, pp. 933–941.

[67] T. Kobayashi, H. Matsuoka, and S. Betsumiya, “Flying communication server in case of a largescale disaster,” in *Computer Software and Applications Conference (COMPSAC), 2016 IEEE 40th Annual*, vol. 2. IEEE, 2016, pp. 571–576.

[68] R. Spica, P. R. Giordano, M. Ryll, H. H. Bülthoff, and A. Franchi, “An open-source hardware/software architecture for quadrotor uavs,” *IFAC Proceedings Volumes*, vol. 46, no. 30, pp. 198–205, 2013.

[69] E. Troncoso, N. Lapeña-Rey, and O. Valero, “Solar-powered hydrogen refuelling station for unmanned aerial vehicles: Design and initial ac test results,” *International Journal of Hydrogen Energy*, vol. 39, no. 4, pp. 1841–1855, 2014.

[70] R. M. Tiwari, “Study on googleës loon project,” *Signal*, vol. 250, p. 10mW.

[71] S. Katikala, “Google™ project loon,” *InSight: Rivier Academic Journal*, vol. 10, no. 2, 2014.

[72] Google, “Google’s balloon powdered internet- some interesting facts!” [Online]. Available: https://thechirpingsoul.com/tag/google/

[73] S. Humphreys, R. Deyermond, I. Bali, M. Stevenson, and J. Fee, “The effect of high altitude commercial air travel on oxygen saturation,” *Anaesthesia*, vol. 60, no. 5, pp. 458–460, 2005.

[74] F. Ahdi and S. Subramaniam, “Using unmanned aerial vehicles as relays in wireless balloon networks,” in *2015 IEEE International Conference on Communications (ICC)*. IEEE, 2015, pp. 3795–3800.

[75] M. ZUCKERBERG, “The technology behind aquila.” [Online]. Available: https://www.facebook.com/notes/mark-zuckerberg/the-technology-behind-aquila/10153916136506634/

[76] A. C. Martin Luis Gomez, “Flying aquila: Early lessons from the first full-scale test flight and the path ahead.” [Online]. Available: https://code.facebook.com/posts/268598690180189

[77] T. swiss foundation, “Resilience amid the struggle - one year on from cyclone winston.” [Online]. Available: http://www.radionz.co.nz/international/pacific-news/324871/resilience-amid-the-struggle-one-year-on-from-cyclone-winston

[78] P. MEIER, "Uavs and humanitarian," *DRONES AND AERIAL OBSERVATION: NEW TECHNOLOGIES FOR PROPERTY RIGHTS, HUMAN RIGHTS, AND GLOBAL DEVELOPMENT A PRIMER*, p. 57, 2015.

[79] F. A. Administration, "Registration and marking requirements for small unmanned aircraft." [Online]. Available: https://www.federalregister.gov/documents/2015/12/16/2015-31750/registration-and-marking-requirements-for-small-unmanned-aircraft

[80] P. J, "Around rarotonga." [Online]. Available: http://www.peterjoiner.com/cook-islands/around-rarotonga/

[81] M. of Finance and E. Managemrnt, "Census of population and dwellings 2011." [Online]. Available: http://www.mfem.gov.ck/statistics/census-and-surveys/census/143-census-2011

[82] O3B, "Telecom cook islands customer story." [Online]. Available: https://www.o3bnetworks.com/telecom-cook-islands/#top

[83] P. J. Webster, G. J. Holland, J. A. Curry, and H.-R. Chang, "Changes in tropical cyclone number, duration, and intensity in a warming environment," *Science*, vol. 309, no. 5742, pp. 1844–1846, 2005.

[84] C. I. G. Australian Government, "Pacific climate change science program." [Online]. Available: http://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/9_PCCSP_Cook_Islands_8pp.pdf

[85] P. I. A. G. Commission, "National action plan for disaster risk management 2009 – 2015." [Online]. Available: http://www.preventionweb.net/files/21869_17857finalnapdocument200920155b15d1.pdf

[86] ——, "Aitutaki island drm plan 2014-2015." [Online]. Available: http://www.emci.gov.ck/wp-content/uploads/2015/02/Aitutaki-Island-DRM-Plan-2014-2015.pdf

[87] C. I. Government, "Evacuation centres." [Online]. Available: http://www.emci.gov.ck/?page_id=364

[88] A. G. B. of Meteorology, "About tropical cyclones." [Online]. Available: http://www.bom.gov.au/cyclone/about/

[89] G. Mao, B. D. Anderson, and B. Fidan, "Path loss exponent estimation for wireless sensor network localization," *Computer Networks*, vol. 51, no. 10, pp. 2467–2483, 2007.

[90] N. Uchida, N. Kawamura, T. Ishida, and Y. Shibata, "Proposal of autonomous flight wireless nodes with delay tolerant networks for disaster use," in *Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), 2014 Eighth International Conference on*. IEEE, 2014, pp. 146–151.

[91] R. O. Schoeneich, M. Golański, B. Krok, and P. Czermiński, “Autonomous drone for delay-tolerant networks in indoor applications,” *International Journal of Distributed Sensor Networks*, vol. 12, no. 8, p. 1550147716662755, 2016.

[92] F. U. Khattak, “Delay tolerant networks in rural areas,” 2005.