Summer 9-2017

Modeling the Use of an Airborne Platform for Cellular Communications Following Disruptions

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MODELING THE USE OF AN AIRBORNE PLATFORM FOR CELLULAR COMMUNICATIONS FOLLOWING DISRUPTIONS

By

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A Dissertation Submitted to the College of Aviation
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Aviation

Embry-Riddle Aeronautical University
Daytona Beach, Florida
September 2017

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ABSTRACT

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Title: MODELING THE USE OF AN AIRBORNE PLATFORM FOR CELLULAR COMMUNICATIONS FOLLOWING DISRUPTIONS

Institution: Embry-Riddle Aeronautical University

Degree: Doctor of Philosophy in Aviation

Year: 2017

In the wake of a disaster, infrastructure can be severely damaged, hampering telecommunications. An Airborne Communications Network (ACN) allows for rapid and accurate information exchange that is essential for the disaster response period. Access to information for survivors is the start of returning to self-sufficiency, regaining dignity, and maintaining hope. Real-world testing has proven that such a system can be built, leading to possible future expansion of features and functionality of an emergency communications system.

Currently, there are no airborne civilian communications systems designed to meet the demands of the public following a natural disaster. A system allowing even a limited amount of communications post-disaster is a great improvement on the current situation, where telecommunications are frequently not available. It is technically feasible to use an airborne, wireless, cellular system quickly deployable to disaster areas and configured to restore some of the functions of damaged terrestrial telecommunications networks.

The system requirements were presented, leading to the next stage of the planned research, where a range of possible solutions were examined. The best solution was selected based on the earlier, predefined criteria. The system was modeled, and a test

system built. The system was tested and redesigned when necessary, to meet the requirements.

The research has shown how the combination of technology, especially the recent miniaturizations and move to open source software for cellular network components can allow sophisticated cellular networks to be implemented. The ACN system proposed could enable connectivity and reduce the communications problems that were experienced following Hurricane Sandy and Katrina. Experience with both natural and man-made disasters highlights the fact that communications are useful only to the extent that they are accessible and useable by the population.

DEDICATION

Undertaking this research study has been an invaluable learning experience. By looking at the development of aviation as a platform to support wireless communications, the author has gained some understanding of the nature of research and of the cyclical and iterative process that is the challenging nature of the investigation process. When carrying out the research, things did not fit neatly into categories, and the exploration could be frustrating and sometimes tedious yet at other times immensely rewarding and even exhilarating.

The experience of successfully using an airborne platform as a self-contained communications system was a culmination of several avenues of research in the area of aviation combined with telecommunications.

ACKNOWLEDGEMENTS

To my grandfather John Wickham to whom I owe my energy and stubbornness. To my parents, Maurice and Ann Curran for their direction and understanding throughout my life. To my partner Junel McFarlane for her support, both overt and covert, throughout the Ph.D program.

To my advisor Dr. Dothang Truong for his wise counsel through this journey. Thank you also to my entire committee for their hard work, advice, quick response, and guidance through the dissertation phase of the program.

Finally, to Dr. Mark Friend, without whom, I have no doubt, I would not have completed the dissertation. As Isaac Newton said, "If I have seen further, it is by standing on the shoulders of giants."

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CHAPTER I

INTRODUCTION

It is important that survivors of any disaster know how, when, and where aid services can be accessed; what is going on around them; and how they can connect with aid providers (Quintanilla, 2013). Yet, in the wake of a disaster, infrastructure can be severely damaged, hampering communications (Nateghi, 2012). On the afternoon of January 12, 2010, the country of Haiti was rocked when a 7.0-magnitude earthquake devastated the nation, resulting in at least 200,000 fatalities (Jackson, 2010). The cellular telecommunications networks were severely damaged by the earthquake. It took five days to bring 70% of the largest cellular operators' sites back on the air; most of the cell sites that remained off-air were in the capital Port au Prince (Digicel, 2010).

Another natural disaster struck on October 29, 2012, when Hurricane Sandy made landfall over the northeastern United States and caused massive damage to buildings as well as key infrastructure related to power, transportation, and communication (Asentria, 2013). Due to damage caused by flooding, high winds, or electrical-grid power outages, large numbers of cell sites over a vast area were inoperative immediately after the storm. In quantifying the network damage caused by Hurricane Sandy, David Turetskty, the Chief of Public Safety & Homeland Security Bureau at the Federal Communications Commission, said, "At the peak of the storm, about 25 percent of cell sites went out of service over the area that we were tracking closely, which included all or part of 10 states and the District of Columbia. In some of the hardest hit counties within New Jersey and New York, however, the outages were more than double that figure" (Turetskty, 2013, p. 4).

Hurricane Katrina was another natural disaster that caused widespread damage to infrastructure. Included in the report *Federal Responses to Hurricane Katrina: Lessons Learned* is a quote by Louisiana State Senator Robert Barham, who holds the position of chairman of the state senate's Homeland Security Committee. Barham summed up the situation in Louisiana post-hurricane by stating, “People could not communicate. It got to the point that people were literally writing messages on paper, putting them in bottles, and dropping them from helicopters to other people on the ground” (Townsend, 2006, p. 37). Local emergency response officials found it difficult or impossible to establish functioning incident-command structures in these conditions. Such structures would have better enabled local response officials to direct operations, manage assets, obtain situational awareness, and generate requests for assistance to state authorities. Without an incident command structure, it was difficult for local leaders to guide the local response efforts, much less command them (Townsend, 2006). A U.S. House of Representatives report summarized the consequences of the failure of communications following Hurricane Katrina by stating:

> The near total failure of regional communications degraded situational awareness and exacerbated problems with agency coordination, command and control, logistics, and search and rescue operations. Without functioning communications systems, first responders and government officials cannot establish meaningful command and control, nor can they develop the situational awareness necessary to know how and where to direct their response and recovery efforts. Similarly, without the ability to call for help, citizens cannot seek emergency assistance,

alert responders or others to their whereabouts and needs, or receive updates or instructions from officials. (Miller, 2006, p. 198)

Townsend and Moss (2005) stated the three main consequences of communications breakdowns were: paralysis of the official responses to the disaster, failure to stop the spread of the effects of the disaster, and a delay in the mobilization of relief efforts.

The earlier examples show how communications failures in the wake of natural disasters hampered rescue and recovery efforts. The vulnerability of telecommunications networks is due to the fact these systems do not have a high degree of resilience. A telephone network, fixed or cellular, utilizes a branching structure in that the destruction of a single network segment can disconnect entire neighborhoods instantaneously (Townsend and Moss, 2005).

Manned aircraft in the military world have long been used for reconnaissance and surveillance purposes. As a platform, manned aircraft offer the advantages of flexibility, quick response, and survivability in a hostile environment (Kumar, 1997, p. 28). Certainly, missions that require the use of human inductive reasoning for survival are still outside the purview of Unmanned Aerial Vehicles (UAVs). The advantages of UAVs in the reconnaissance role are cost, the capacity to undertake missions where expendability is an issue, and endurance (Kumar, 1997, p. 28). In the civilian application of telecommunications, it is unlikely that a UAV would be considered as a target and be threatened with destruction.

UAVs and manned aircraft are deployed to accomplish such missions as Intelligence, Surveillance, and Reconnaissance (ISR) to Border Patrol, Emergency

Response support, and Environmental Monitoring (Newtec, 2013). In flier's language, UAVs are best for "dull, dirty, and dangerous" missions (Chopra, 2013).

There have been attempts to use aircraft to provide telecommunications services to terrestrial customers. The company QucomHaps conducted research using M55 aircraft as a host for a cellular communications network (QucomHaps, 2016). To date, the company has not launched a commercial service.

As technology advances in the field of aviation, there is increasing attention on UAVs not only in the military arena, but in the civilian domain as well. Unmanned aerial vehicles and systems continue to grow in sophistication and complexity. The advantages of using a UAV, relative to the use of a manned aircraft, are that the UAV does not contain or need a qualified pilot on board, and the endurance of a UAV is not constrained by the physiological limitations of a human pilot (UAVS, 2016). A UAV can perform a precise, repetitive orbit of a region, day-after-day, night-after-night, in complete darkness or in fog, under computer control. The UAV can be programmed to complete the mission autonomously of ground control. A UAV with the appropriate communications payload can be quickly moved and rendered operational in a disaster area.

There is academic research into airborne, low-altitude systems for Global System Mobile (GSM) communications using an off-the-shelf, GSM mini-base station mounted on a small UAV (Wypych, 2012). For Wypych's research, the cellular network was not fully autonomous in that the core network call processing was done on the ground via a Wi-Fi radio link from the UAV. Wi-Fi is a wireless technology that is not as sophisticated as a cellular GSM type network. Wi-Fi uses unlicensed spectrum that is subject to interference from other users; whereas, cellular spectrum is more tightly regulated and is exclusively allocated to each individual cellular network operator. The height and range of operation of the cellular network was limited by the small size of the UAV. The size of the UAV limited the system's payload and hence the overall capability of the system.

Tuna, Nefzi, and Conte (2014), in their research on a UAV-aided communications system for disaster recovery, acknowledge from their own review of the literature that current studies fall short in some respects, such as a lack of field tests or experimental validation of using UAV's for communications. The report authors noted tests were critical to demonstrate the practicality of the solution to real-world scenarios.

Emergency communications can be used to alert the population after a disaster, convey necessary information to allow important decision-making during all the phases of the disaster, and allow for better coordination during the event among the different response entities (ITU, 2014). An airborne radio-based wireless system, however, has the potential to be deployed quickly to the disaster areas and could be configured to replicate some of the functions of the damaged terrestrial network (Valcarce et al., 2013).

Significance of the Study

In the immediate aftermath of disasters, from natural calamities to armed conflicts, a principle fact in survival is knowing the answers to questions such as: Is it safe to go back home? Where are family and friends? How and where is help available (Quintanilla, 2013)? Access to this information is the start of returning to self-sufficiency, regaining dignity, and maintaining hope. The impact of this crucial knowledge can be life-saving (Quintanilla, 2013). The impact of a disaster on a country's telecommunications infrastructure can be immense, with the cell phone towers being completely destroyed or the equipment on the towers being badly damaged. Power and fuel supplies can be disrupted (Ran, 2010).

During the recovery from the Haiti earthquake, the Haiti Red Cross Society and International Federation of Red Cross and Red Crescent Societies (IFRC) developed a range of software tools that created a dialogue between staff and volunteers working in the region and those they were attempting to support. The benefits of two-way communications are that the aid agencies can establish what support people need and, as importantly, what they do not need, to better ensure communities get the correct assistance (International Federation of Red Cross and Red Crescent Societies, 2013). Bartolacci, Mihovska, & Ozceylan argued having temporary base stations available to first responders or an affected populace immediately following a disaster would provide a common picture of an emergency situation to allow for a more rapid and coordinated response (Bartolacci, Mihovska, & Ozceylan, 2013).

Shao, Liu, Wu, & Shen (2011) proposed a model of an aerial wireless emergency communication system to be used in a disaster area, satisfying the need for rapid and reliable communication with the outside world. The system described by the authors is theoretical in nature and requires ground-based equipment for the system to function. This dissertation investigates using an autonomous airborne-telecommunications system operating without the need for any ground telecommunications equipment.

Statement of the Problem

Currently there are no airborne civilian communications systems designed to meet the demands of the public following a natural disaster. A system allowing even a limited amount of communications post disaster will be a great improvement on the current situation, where all communications are frequently not available (Ran, 2011).

This dissertation includes a quantitative and qualitative study to determine the technical feasibility of using an airborne, wireless, cellular system quickly deployable to disaster areas and configured to restore some of the functions of damaged terrestrial networks.

Purpose Statement

The purpose of the research is to model how an airborne communications system could be used to facilitate communications in a scenario such as the aftermath of a natural disaster. The Airborne Communications Network (ACN) is a system that will facilitate emergency communications in the aftermath of a disaster. The ACN has a set number of possible users within a specific coverage area and will offer a defined set of services. The system is designed to offer communications facilities in the event of a complete failure of the ground-based cellular network in the wake of a catastrophic event.

Research Question

The following research question was posited for this investigation: How can an airborne emergency wireless communications system be modeled to provide design guidance on cellular communications service for use by the general public in disaster-aftermath related scenarios?

Tuna, Nefzi, and Conte (2014) acknowledge that from their own review of the literature, current studies fall short in some respects, such as a lack of field tests or experimental validation of using UAVs for communications. Emergency communications can alert the population after the disaster, convey necessary information to allow important decision-making during all the phases of a disaster, and allow for better coordination during the event among the different response entities.

Delimitations

The research was narrowed in order to focus on certain areas. The system only facilitates text communications point-to-point between users registered on the ACN. It does not allow voice calls or data sessions and does not allow text messages to be sent outside the network itself. These delimitations are being put in place in order to ensure the scope for the project is specific, measurable, achievable, and realistic. While a more complex system involving the ACN supporting other services such as voice and internet access would provide more services, the complexity of such a system would make it difficult to implement in a timely manner for this research. Similarly, only a single Airborne Communications Platform (ACP) is considered rather than a fleet of ACPs, to extend the potential coverage of the network. A mesh or network of ACPs would increase the complexity of the research.

For the purposes of the research, a defined test case of a relatively small Caribbean island or part of a larger island was examined. The research did not delve into the merits of different types of UAVs or discuss different UAV technologies.

Limitations and Assumptions

An operational test communications system was placed on board an aircraft and tested while the aircraft was airborne. The duration of the experiment was determined by the electrical power available to support the communications equipment. The experiment itself did not take place in the aftermath of a disaster which led to certain performance issues within the system. Radio interference caused by the existing operational cellular systems caused system performance issues. Due to the limited number of personnel available to run the experiment and economic constraints, test phones on the ground were located in close proximity and not spaced out throughout the test area, as would be the case in a real-life system.

The availability of a suitable antenna on the aircraft was also a factor in the selection of the experimental frequency of operation. The aircraft system antenna was re-tasked for use for this experiment; therefore, the 900 MHz band was selected as the frequency band for the trial.

Definitions of Terms

Airborne emergency wireless communications system – Basic communications system hosted on an airborne platform that allows communication between ground terminals in the event the terrestrial communications network is inoperable.

Backhaul - In a hierarchical telecommunications network, the backhaul portion of the network comprises the intermediate links between the core network, or backbone network, and the small subnetworks at the "edge" of the entire hierarchical network.

Cellular communications service - System for allowing communication between suitable user terminals.

Disaster-aftermath-related scenarios – The situation post disaster where the electrical grid and terrestrial communications networks can all be offline.

General public – People located in the disaster area in possession of a working compatible cellular phone. This is the potential population for the emergency system.

List of Acronyms

ABSOLUTE	Aerial Base Stations with Opportunistic Links for Unexpected and Temporary Events
ACN	Airborne Communication Network
ACP	Airborne Communications Platform
AP	Airborne Platform
ARFCN	Absolute Radio Frequency Channel
BACN	Battlefield Airborne Communications Node
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
CB	Cell Broadcast
CDMA	Code Division Multiple Access
dB	deciBel
DME	Distance Measuring Equipment
E	Erlang
EBAN	Emergency Broadband Access Network
E_b/N_0	Energy per bit to the Spectral Noise Density
FAA	Federal Aviation Administration
FCC	Federal Communications Commission

Gbps	Gigabit per second
GPS	Global Position System
GSM	Global System Mobile
HAP	High Altitude Platform
HLR	Home Location Register
HTS	High-Throughput Satellite
IFRC	International Federation of Red Cross and Red Crescent Societies
ITRI	Industrial Technology Research Institute
Kbps	Kilobits per second
Km	Kilometers
LAP	Low-altitude Aerial Platform
LTE	Long Term Evolution
LOS	Line of Sight
MANET	Mobile *ad hoc* Network
MS	Mobile Station
MSC	Mobile Switching Center
NLOS	Non-Line of Sight
NSS	Network Subsystem
PBX	Private Branch Exchange
PSAP	Public Safety Answering Point
SDCCH	Standalone Dedicated Control Channel
SMS	Short Message Service
SMS-C	Short Message Service Center

RX	Receive
TCH	Traffic Channel
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
TRX	Transmitter Receiver Module
TX	Transmit
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UMTS	Universal Mobile Telecommunications System
UPS	Uninterrupted Power Supply
VLR	Visitor Location Register
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity Wireless Internet
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER II

REVIEW OF THE RELEVANT LITERATURE

Critical to understanding how new developments or ideas can be introduced concerning a research topic is the review of the existing work in the field of emergency communications. Knowledge of how researchers have explored the subject matter and review of their work can lead to areas of new research. Once a detailed description of the current state of research is established, conducting *what if* scenarios can be used to see where there are areas of interest for the expansion and trial of new ideas in the area of research.

The concept of using an airborne platform to host communications systems is not new. Early origins of balloons being used for signaling trace back over 2,000 years to China and a device known as the sky lantern. Zhuge Liang lived in China in the second century BC and has been credited as one of the earliest inventors of the hot air balloon (Zhugeliangnet, 2014). Zhuge Liang was a politician and strategist during the Three Kingdoms Period. Trapped during a battle, Zhuge Liang was said to have released a paper lantern with a message on the paper cover. Nearby friendly forces discovered the sky lantern and came to his aid (Deng, 2005). The sky lantern was made of rice paper on a bamboo frame. A candle or combustible material was used to supply the hot air needed to provide lift. The sky lantern was an early example of an airborne platform used as a means of communication.

As another example of early airborne communications, the French Montgolfier brothers conducted experiments in the late eighteenth century with hot air balloons (Tucker, 2010). The first untethered human flight occurred on November 21, 1783, just outside Paris. During the Franco-Prussian War's Siege of Paris, the French sent balloons with messages out of the besieged city (Tucker, 2010).

In the current decade, a platform such as the Battlefield Airborne Communications Node (BACN), made by Northrop Grumman, provides a gateway in the sky that receives, bridges, and distributes military radio communication among all participants in a battle (Lamar, 2015). In operational environments, mountainous terrain inhibited line-of-sight communications; diverse weapon systems were unable to communicate with each other; and each operating unit could see only a limited set of the complete picture. BACN bridges the gap between those systems, enabling essential situational awareness from small ground units in contact up to the highest command levels. The BACN system is a military system designed with a specific objective. The principle could be applied to a civilian communications system, and such a system is not currently available.

Effects of a Disaster

The main reasons for telecommunications failures are the physical destruction of the network components, the disruption of the supporting network infrastructure such as the power grid, and network congestion (Pace & Aloi, 2008). Mobile cellular communications help to coordinate the recovery efforts in the disaster zone and connect the zone to the rest of the world. An airborne platform with a suitable communications suite could be designed for short-term recovery of cellular communications during the critical period following a disaster.

Hurricane Katrina caused extensive flooding and major damage from the strong winds (Victory, 2006). More than one thousand cellular base stations were damaged by the storm, with the major impact being caused by the lack of commercial power and the loss of transmission connectivity back to the wireless switch at the central office (Victory, 2006). The main impediments to network recovery noted by Victory (2006) were limited access to back up generators and fuel, limited security for infrastructure and personnel, lack of pre-positioned spare parts; and lack of co-ordination between various industry and government officials. These impediments to the recovery of communications could be largely circumvented by using an airborne system in the immediate aftermath of the disaster.

Hurricane Sandy left thousands without access to communications networks (Wood and Martines, 2012). Cellular phones and phones that run over an internet connection were especially unreliable and unavailable after the storm. This was because cell towers are vulnerable to damage caused by strong winds and failure of the electric grid. Home broadband connections depend on the power grid, and if this supply fails, the connection is often unusable. Most cell towers are equipped with backup generators, but these generators may not start, may run out of fuel, or may be subject to theft. An airborne platform can be brought on station from another location to replace the ground infrastructure during the terrestrial network restoration phase.

A further example of widespread damage to cell phone services occurred in May 2013 when a huge tornado ripped thorough Oklahoma City (Smith, 2013). The wireless service providers urged customers to use text messages instead of voice calls as messaging puts less strain on the network resources. Sprint spokesperson Crystal Davies said, “We’re asking them to use text messaging versus voice, as the recovery and response efforts continue” (Smith, 2013). A text-based emergency communications system will be shown in this research to be an efficient method of communicating in the high-usage period following a disaster.

Functioning communications infrastructure is critical to managing the changing and chaotic environment that exists following a disaster. Hurricane Katrina destroyed the communications infrastructure within the New Orleans region, leaving emergency response personnel and the public with little ability to exchange information vital for coordinating response actions (Comfort & Haase, 2006). Cell sites were flooded, rendering cell phones inoperable (Comfort & Haase, 2006). For the three days following the landfall of the storm, there was no reliable means of communications among local, state, and federal organizations seeking to coordinate the rescue and recovery operations (Comfort & Haase, 2006).

When a major disaster strikes sites, aid and rescue workers converge on the disaster area from all around the world. Frequently, rescue and aid works are hindered by lack of communications systems. Victims can usually survive for 72 hours if trapped under a collapsed building or if isolated by a flood (Lee & Choi, 2011). If cellular telecommunication service can be restored in a timely manner, victims can perhaps contact emergency service so rescue workers can reach and assist them. Following restoration of service, the rescue workers can communicate with each other to more effectively coordinate the rescue work.

Features of an Emergency Communications System

An emergency communications system should be reliable, robust, easily configurable, quickly deployable at a relatively low cost, useable for a range of disaster, and interoperable with existing devices (Dilmaghani & Rao, 2008). The system should also be able to function with the minimum amount of dependencies on other equipment. Dilmaghani & Rao (2008) also noted text messaging is a suitable alternative to voice and exchange messages after a disaster when there could be congestion on the voice network. In an earlier paper, Dilmaghani & Rao (2007) noted another key factor of planning the response to an emergency is whether the disaster has been predicted. There is normally forewarning of the approach of a hurricane, but in contrast, a disaster such as an earthquake strikes without notice. In the case of advance warning of an impending disaster, steps can be taken to pre-position emergency response equipment such as an Airborne Communications Network (ACN), to a location close to, but out of the potential path of the pending disaster.

Network congestion in the period following a disaster can render a functional telecommunications network useless (Townsend & Moss, 2005, p. 12). The earthquakes at Kobe in 1995, San Francisco in 1989, and Los Angeles in 1994 showed telephone networks are not so much destroyed as congested and overloaded into uselessness (Noam & Sato, 1996). This research was mindful that congestion is a serious issue potentially harming the effectiveness of the ACN. Strategies were developed to mitigate the potential gridlock congestion could cause the ACN system.

Current Communications Systems

In the last 20 years, the coverage and services offered by public safety systems, such as land mobile radio systems, have lagged behind commercial systems such as GSM (Habib & Mazzenga, 2008). GSM has become almost ubiquitous and compared to specialist public safety systems has a much wider deployment and subscriber base. In Switzerland, the air rescue helicopters have had GSM fixed phones installed in addition to aeronautical radios, due to the superior coverage and far greater number of cell sites of the GSM network compared to the nationwide emergency radio network (Kurz, 2000).

The state-of-the-art of telecommunications networks today is a technology called LTE (Long Term Evolution). An LTE base station is referred to as an *enode B*, and Gomez et al. (2013) discussed the hosting of an enode B on an airborne platform. Modeling and performance analysis with a platform deployment of a single airborne communications platform indicates that airborne units with LTE communication capabilities are very promising candidates for robust communication links during emergency relief operations (Gomez et al., 2013). LTE technology does not enjoy widespread deployment, and the technology is not suitable as a mass-market communications solution, at the present time.

In terms of similarity with the research subject matter of using UAVs for communications, the closest research found was presented in the master thesis *GSM Network Employment on a Man Portable UAS*, by Darren Rogers (2012). This thesis provided an overview of the history of UAVs and an introduction to the GSM system. Rogers continued to build a test GSM system using technology very similar to that proposed for use by this researcher. The exact mode employed by the author is not clear in the thesis, and unfortunately, the author could not mount the telecommunications equipment on a UAV due to time and regulatory issues.

Wypych, Angelo, & Knester (2012) describe a system for GSM communications using an off-the-shelf GSM mini base station mounted on a small UAV. The UAV was not a fully autonomous communications platform in that the core network switching and processing of the voice calls was performed on the ground. Communication was passed via a Wi-Fi radio link between the UAV and the ground station. The range and altitude of the communications system were also limited by the small size of the UAV. System payload in the trial was restricted by the limited capability of the UAV. The equipment mounted on the UAV was limited, hence the overall capability of the system was restricted to being a cell site in the air, without the full network-in-a-box concept. As a very simple basic demonstration of the technology and general concept of airborne communications, the paper is very relevant and is extended by the research in this dissertation.

Existing Research on the Topic

Guevara et al. (2015) developed a UAV-based GSM network for communications. A GSM station was mounted on a quadcopter, but the researchers did not publish test results of the operation of the system. The paper did not state if the system is fully autonomous or if ground equipment is needed for the telecommunications portion of the system. The UAV the researchers used was controlled via remote control from the ground or by receiving the navigation coordinates as inputs. Guevara used the same OpenBTS network-in-a-box solution that this researcher proposed to use.

The OpenBTS network-in-a-box was used as a test bed for research into the voice quality and coverage of a GSM emergency network (Garcia, Angule, and Muskus, 2014). The paper compared the Okumura-Hata, Walfisch-Ikegami, and Friis radio propagation models for predicting the likely coverage from a small test network. The central processor load of the network-in-a-box and the blocking probability were also calculated. The results of Garcia, Angule, and Muskus are useful to the current research as a comparison with the results of this research.

An *ad hoc* network can provide reliable and robust communications, as it does not need an infrastructure backbone or link to the outside world (Fragkiadakis, 2011). A *mobile ad hoc network (MANET)* has the advantage that communications nodes can be interlinked without the need for pre-existing infrastructure.

In the aftermath of a disaster, multiple agencies need to operate collaboratively on the rescue site using reliable and interoperable communication systems (Valcarce et al., 2013). Valcarce proposed that new architectures were needed to provide flexible, scalable, resilient, and secure broadband access. Based on a rapidly deployable airborne platform with an onboard base station, a proposed system called *Aerial Base Stations with Opportunistic Links for Unexpected and Temporary Events (ABSOLUTE)* would be able to quickly deploy cellular networks with wide local coverage. This system proposes to combine multiple airborne, terrestrial, and satellite systems. The ABSOLUTE project is funded by the European Union, and the main goal of it is to design and validate a network architecture that will allow communication services based on the following main features: rapid deployment, flexibility, scalability, and seamless re-configurability. The project aims to provide broadband services with the necessary resilience, availability, and security. The project is using the more advanced LTE standard in combination with advanced satellite communications and current public safety networks (ABSOLUTE, 2015).

Hariyanto, Santoso, &Widiawan (2009) carried out a measurement campaign in the field for an *Emergency Broadband Access Network* (EBAN) based on a Wi-Fi router attached to a balloon. The balloon used in the experiment utilized hydrogen gas and had a dwell time on-station of three days. From their measurements, they verified an EBAN model and then provided coverage analysis extrapolated from the validated EBAN system model.

Host Platforms

High Altitude Platforms (HAPs) are aircraft or airships operating in the stratosphere at altitudes of 17 to 22 km (Abbas, Arnon, Grace, Mondin, & Miura, 2008). At this altitude, HAPs can maintain a quasi-stationary position and support payloads that support communications and remote sensing. Communications services can include mobile cellular telephone, wireless broadband, and broadcast services. This research examines the use of platforms with a lower altitude of operations in the order of hundreds of meters. A lower operational altitude will result in the airborne platform having a reduced coverage area and limits the communications range of the platform. Reducing coverage can be useful, as this limits the number of users accessing the system. The coverage limitation provides a method to control access to the system and reduces the chances of system congestion and overload.

Low-altitude aerial platforms (LAPs) are being researched as key hosts for rapid deployable relief networks where coverage is provided by onboard base stations (Al-Hourani, Kandeepan, and Lardner, 2014). These platforms are capable of delivering essential wireless communication for public safety agencies in remote areas or during the aftermath of natural disasters. Al Hourani et al. determined a mathematical model to establish the ideal altitude of operation of these platforms to provide maximum radio coverage on the ground. Furthermore, the research showed that the geometrical line of sight between an LAP and a ground receiver could be expressed as a closed-form equation, based on the elevation angle and the urban statistical signal path loss parameters.

The paper *Aerial-terrestrial Communications Terrestrial Cooperation and Energy Efficient Transmissions to Aerial Base Stations* discussed how low-altitude platforms are expected to meet the urgent communication needs of emergency operations (Kandeepan, 2014). The research discussed the design and evaluation of a system with special consideration of the electrical power consumption, and proposed an adaptive cooperative scheme intended to extend the survivability of the battery-operated, aerial-terrestrial communication links. The system performance was modeled and simulated in a manner that this researcher emulated for some of the research.

Researchers have previously discussed many aspects of using an airborne system for emergency communications. The paper *High Altitude Platforms for Disaster Recovery: Capabilities, Strategies, and Techniques for Emergency Telecommunications,* provided an overview of how a HAP-based communications system could be used in the aftermath of a disaster (Deaton, 2008). The author makes communications traffic calculations for system dimensioning, based on likely call volumes to the emergency services. The paper continues by discussing the Federal Communications Commission (FCC) mandated Emergency 911 system used to locate emergency callers and the difficulty of implementing this system on a HAP. Deaton prefers the Code Division Multiple Access (CDMA) cellular technology to the GSM system, due to the technical superiority of the CDMA system.

Choice of Mobile Cellular Technology

This dissertation concentrates on the GSM system, due to GSM's ubiquity with 6 billion of the world's 6.7 billion cellular subscriptions using the GSM system or its subsequent derivatives (Qureshi, 2014). LTE and Wideband Code Division Multiple Access (WCDMA) are considered upgrades to the GSM system, and all LTE and WCDMA handsets are backward compatible with the GSM standard (Onetouchmobility, 2013).

CDMA may be a superior cellular system from a technology point of view, but it has not gained as widespread usage as the GSM system. Figure 1 shows the adoption rates worldwide of the different technical mobile cellular phone standards. In the case of a disaster, an emergency system should be accessible by as many people as possible. During an emergency, it is more likely people will use the most widespread communications system already available, rather than a more sophisticated system that takes time to deploy (Hariyanto, Santoso, & Widiawan, 2009).

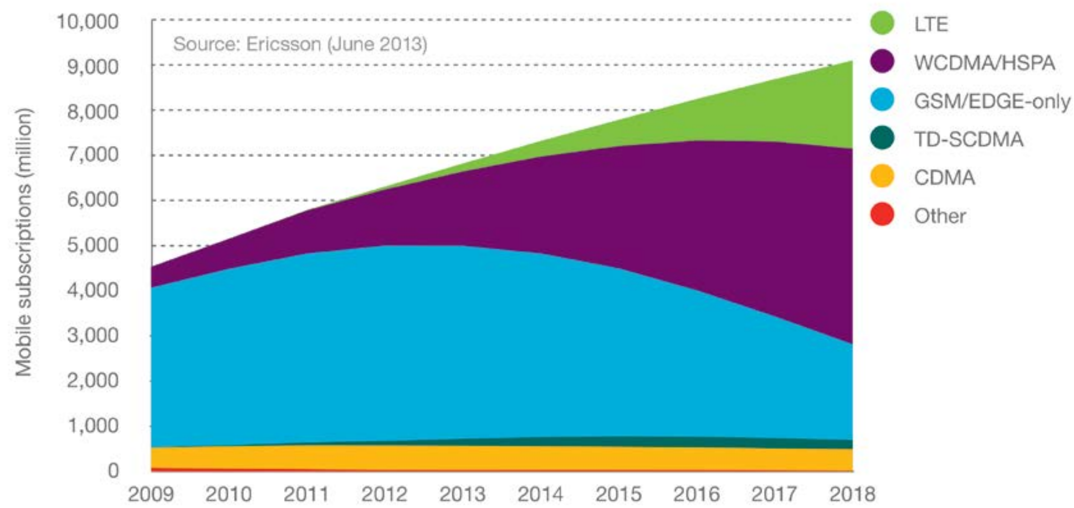

Figure 1. Mobile cellular subscriptions by technology, 2009-2018. Adapted from "Mobile Subscriptions," n.d. Retrieved from http://hugin.info/1061/R/1706363/564795.jpg

The Universal Mobile Telecommunications System (UMTS)/WCDMA system is a third-generation cellular communications system for networks based on the GSM standard (Onetouchmobility, 2013). A case study for an airborne system based over Madrid, Spain, shows the city can theoretically be covered by a HAP with 169 UMTS cells on board (Taha-Ahmed, Calvo-Ramon, & de Haro-Ariet, 2005). For a HAP with 169 cells or beams, the total practical capacity of the system would be in the order of 10,000 simultaneous voice users or 1,250 data users. Using UMTS instead of the previous generation GSM system is attractive from a system capacity and performance point of view, but UMTS technology is not as robust or as widely deployed as the older GSM technology. The system proposed could be operated as a network-in-a-box supporting just voice and Short Message Service (SMS) communications, but UMTS is better suited to the provision of internet access. As such, the HAP would need a connection either via a satellite or terrestrial link to obtain an onward connection to the internet. A UMTS system would be a much more complex system than the GSM network-in-a-box based system of this dissertation.

In research carried out by Vodafone and analyzed by Trosby (2010), typically 38% of SMS messages were not delivered on the first attempt to the end user. This result was due to the receiving cell phone being out of coverage, in poor coverage, or turned off. The overall success rate of messages eventually delivered was 98% (Trosby, 2010, p. 121). These key performance indicators can be used to help craft the system performance model.

The network-in-a-box in the current available configuration does not have a billing system, so users will not be charged for the SMS messages that are sent. There is a risk of serious network congestion if a service that is usage fee based is made available free of charge to users. The average SMS messages per user in the Digicel Jamaica network is 0.8 SMS per user per hour according to C. Henry (personal communication, August 10, 2015). A mechanism to limit the number of SMS messages that can be sent per user per time period will have to be investigated as part of this research.

The Short Message Service is a special type of messaging implemented as an integral part of the signaling system of the GSM standard and was proposed in the specification as the only new service that did not already exist in public, fixed networks (Trosby, 2010, p. 10). There are two GSM network elements that process a mobile-originated SMS message. The first network element is the radio access segment between the users' handsets and the cell site. The second network element is the short message center that handles SMS operations, such as routing, forwarding, and storing text messages (Rouse, 2007). The GSM network elements that process an SMS message are shown in Figure 2.

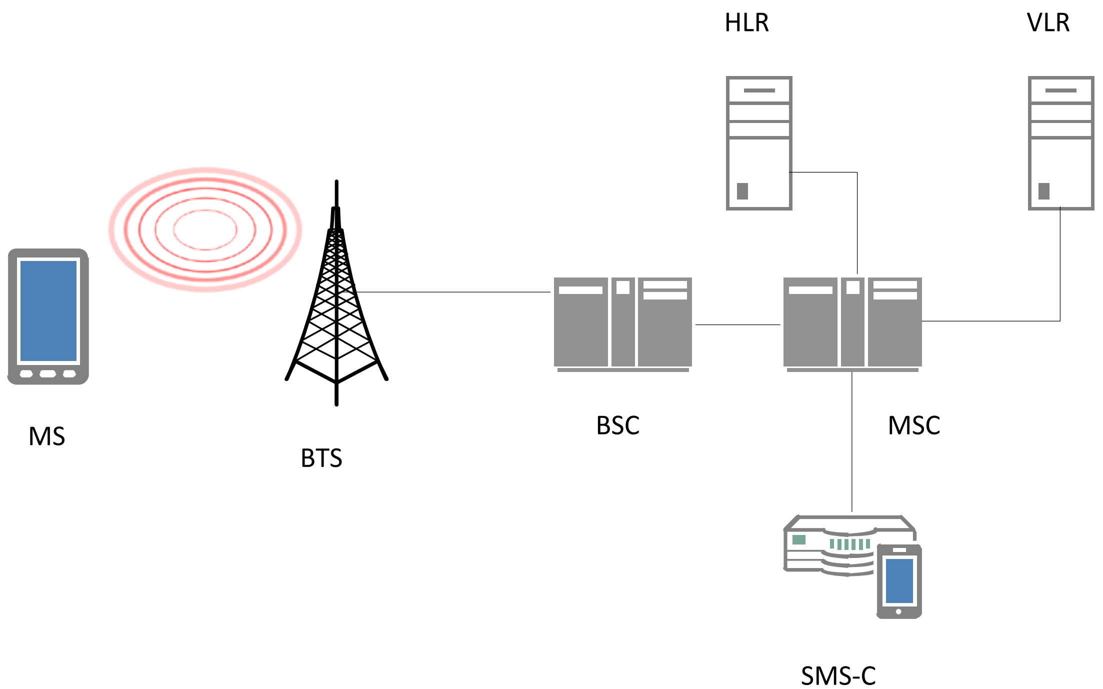

Figure 2. GSM network elements that process an SMS message.

The *Mobile Station (MS*) is the device or terminal the subscriber uses to send the SMS message; typically, a cell phone. The *Base Transceiver Station (BTS)* is the equipment at the cell site that allows for the physical connection of the cellular phone to the network via the air interface (Heine, 1998, p. 19). The *Base Station Controller (BSC)* controls the operation of a number of individual BTSs. Together the BTS and BSC are referred to as the *Base Station Subsystem (BSS).*

The *Network Switching Subsystem (NSS)* is the central core of a cellular network. The network elements of the NSS provide the control and database functions that allow calls to be connected and messages to be transferred. The *Mobile Switching Center (MSC)* is the component of a GSM system that carries out call switching and mobility management functions for cellular phones. The *Home Location Register (HLR)* is the database that stores the permanent subscriber data of the user. The *Visitor Location Register (VLR)* is the database that stores the information of the connected users and the whereabouts of the user. The entries in the VLR are dynamic and change frequently. The subscriber data in the VLR is valid only when the station is switched on, has network coverage, and has been authenticated. The *Short Message Service Centre (SMS-C)* is the node that takes care of the store-and-forward functionality of messages to and from the mobile station. The airborne communications platform, as envisaged in this research, has all of these network element functions co-located onboard the aircraft operating as a full, standalone network-in-a-box.

The *service system* is the name given to the queuing system as a whole. A queuing model is an abstract description of such a system. The main elements of this system are the number of waiting lines, the number of servers, the arrangement of servers, the arrival and service rates, and the service priority rules. Formulas exist that allow for the computation of statistical estimates for the average number in the queue, the average waiting time for a customer, and the probability that the server is busy. The essence of the queuing theory is that it takes into account the randomness of the arrival process and the randomness of the service process (Cooper, 2000, p. 1496). Offered traffic is measured in units named *Erlang* (E) which is related to the call arrival rate, λ, and the average customer or message processing time h, expressed in Equation 1.

$$E = \lambda h \tag{1}$$

In mathematical terms, the BSS network between the customer handset and the cell site network can be considered as an Erlang loss system. In this type of system, the text messages are assumed to be sent by the customers at random times in what is termed a *Poisson process*, and the customers' blocked messages, those that are sent and then find all servers busy, are cleared. These blocked messages are denied entry into the system. The proportion of arriving messages that find all the servers busy is given by the Erlang loss or Erlang B formula (Cooper, 2000, p. 1497). This formula provides the probability of blocking or loss probability.

The Erlang loss model is one of the fundamental models of tele-traffic engineering. The customers in these calculations are SMS text messages, the servers are network resources, and the blocked SMS messages are cleared from the system, and thus are lost SMS messages. The arrival pattern of SMS messages at the cell site is considered to be random and is described mathematically as following an exponential distribution. In this specific network segment, SMS messages that are blocked by the cell site are lost and not buffered or queued. If there are not enough resources available at the cell site to process the SMS message, then the user is notified that the message sending process has failed.

The Erlang B formula (Equation 2) provides the grade of service, which is the probability P_b that a new SMS message arriving to the cell site is rejected because all resources are busy: B (E, m), where E is the total offered traffic in Erlang offered to m identical parallel resources.

$$P_b = B(E,m) = \frac{\frac{E^m}{m!}}{\sum_{i=0}^{m} \frac{E^i}{i!}} \tag{2}$$

Once the SMS message has moved from the BSS network to the SMS-C in the NSS, then buffering and storage can take place. Modeling an SMS text message in the SMS-C has certain unique features compared to modeling voice or IP data traffic. SMS is memoryless, in that one SMS message is independent of any other SMS in space and time. Unlike voice calls in a telecommunications network, SMS messages, once they have entered the NSS part of the network, can withstand delay. SMS is a store-and-forward technology. If any part of the network between the SMS-C and destination is temporarily unavailable, the SMS message is stored in a buffer and the SMS is not lost. For the SMS-C, as queuing of messages is possible within the network element, the Erlang B formula is not appropriate, and a different model that considers buffering is used. This model is called the *Erlang delay model* and is similar to the Erlang loss model, except that now the blocked SMS message will be buffered in a queue as long as necessary for a server to become available (Cooper, 2000, p. 1497). In this delay model, the probability of blocking is given by the Erlang C formula. The assumptions for the Erlang C formula are that SMS messages arrive in a Poisson process, the service times are exponential, the SMS are dealt with on a first-in first-out basis, and the SMS waiting buffer is sufficiently large (Parkinson, n.d.). The input information for the calculation using the Erlang C formula is the arrival rate, the service rate, and the number of servers as follows in Equation 3:

$$P_W = \frac{\frac{A^N}{N!}\frac{N}{N-A}}{\left(\sum_{i=0}^{N-1}\frac{A^i}{i!}\right)+\frac{A^N}{N!}\frac{N}{N-A}} \quad (3)$$

Where: A is the total traffic offered in units of Erlang, N is the number of servers, and P_w is the probability that a customer has to wait for service. In the Erlang B model, the blocked customers are cleared from the system, whereas in the Erlang C model, the blocked customers enter the system and wait in the queue, thereby increasing the probability that future arrivals will find all the servers busy (Cooper, 2000, p. 1498).

Airborne Communications

One of the main areas of research in airborne communications has been in the use of HAPs. *Broadband Communications via High-Altitude Platforms* is one of the complete books dedicated to the subject of using HAPs for broadband communications (Grace & Mohorcic, 2011). The authors provide an overview of HAP enabling technologies and describe research activities in the field. Grace and Mohorcic focus on placing HAPs in the perspective of current and future broadband wireless communication systems, providing an overview of the constraints affecting HAP-based broadband communications. The economics of HAPs communication systems are discussed, including issues related to aeronautics, operating scenarios, applications, and business modeling. To date, no HAP has been put into service providing live communications services from commercial operators.

The majority of research in the field of airborne communications platforms has been theoretical in nature. Elabdin, Elshaikh, Islam, Ismail, & Khalifa (2006) discuss the advantages of HAPs over terrestrial and satellite architectures and the communications applications of HAPs. The authors state the aim of HAPs is to exploit the potential benefits of intermediate altitudes between those used by the terrestrial and satellite technologies. Compared to terrestrial telecommunication systems, HAPs offer high signal arrival angles and a larger coverage area. Compared to satellites, HAPs do not require any launch vehicles and offer a much shorter signal path. The authors discuss the technical challenges and critical issues of using HAPs of energy source, platform station keeping, modulation, coding, antennas design, propagation, diversity, interference, and handover.

An airborne platform can either be a single unit with no link to the rest of the network or the host of a base station having links to the rest of the core network based on the ground (Kandus, Svigelj, & Mohorcic, 2005). The simplest system configuration consists of a standalone platform, where a network is limited to a single, airborne platform. Only communication between user terminals within the coverage area provided by the network is possible. The authors propose that a standalone airborne platform is suitable for the basic provision services for short time events, such as in the wake of a natural disaster, where the ground based infrastructure has suffered a major failure.

Field experiments were conducted in Slovenia using test ACNs with different radio standards. *Terrestrial Trunked Radio (TETRA)*, *Wi-Fi*, and *Worldwide Interoperability for Microwave Access (WiMAX)* communications technologies were all tested. The ACN was established using a tethered hydrogen balloon (Vilhar, Hrovat, Javornik, & Mohorcic, 2013). The experiments showed the actual boundaries of current wireless technologies by testing their performance in practice. Three experiments were performed with a balloon and a mobile ground station equipped with TETRA, Wi-Fi, and

WiMAX terminals. The results confirmed relatively reliable communications with TETRA technology, up to distances of nine kilometers, as opposed to the relatively short communication range of about one kilometer and a sometimes-unstable operation using Wi-Fi and WiMAX. This dissertation focuses on the GSM technology using SMS as a basic communications medium. TETRA is a specialized communications solution used primarily by the emergency services and as such is not a suitable system for mass communications. Wi-Fi is a low-power data transmission standard not suitable for wide area communications. WiMAX is a data communications standard being phased out in preference for the more modern LTE standard.

El-Jabu & Steele (2001) presented a series of equations quantifying the coverage area on the ground as a function of HAP elevation. Calculations were made of the number of users versus the ratio of *Energy per Bit to the Spectral Noise Density* (E_b/N_0) for different service rates. E_b/N_0 is the measure of signal to noise ratio of a digital communication system (Pearce, 2000). An ACN having cells of different sizes, adjustable based on the offered cellular traffic was examined. An antenna array structure was proposed to achieve beam forming and cell size shaping. The UMTS system was used for the example calculations. The preliminary results of the research showed a HAP operating at an altitude of 21 kilometers could theoretically cover an area with a radius of 517 kilometers. The authors' calculations show up to 21 users per cell with a service rate of 8 kilobits per second (kbps) can be accommodated in the 3.2-GHz frequency band. The 3.2 GHz band is not a standard cellular band currently in use but does have potential to be used when the existing occupants are relocated. These voice and data services could be provided within an area of radius 70 kilometers, with transmitted powers of less than 1 Watt. High system capacity was proved to be possible by constructing cells with a radius as small as 100 meters, using square planar arrays with dimensions of 12 ×12 meters. A 12 x 12 meter antenna array is very large and would need a considerable HAP vehicle to support.

Hasirci & Cavdar (2012) discussed propagation modeling and showed how performance analysis on the HAPs are derived mathematically. The elevation angle is the dominant parameter of the model. All possible propagation environments are divided into four groups: suburban, urban, dense urban, and urban high rise. These terrain types were modeled using well-known statistical models with a dependence on elevation angle. The main parameters of the model were the elevation angle, Rayleigh and Ricean propagation factors, and the percentage of time a given fade depth was exceeded. To observe the effects of the parameters on the model, the correlation coefficients between model parameters and the fade depth are calculated. The new HAP model contains two cases, *line of sight (LOS)* and *non-line of sight (NLOS)* propagation paths between a HAP and a user. In the conclusion section, obtained models are combined with free space path loss and full formulations of total path loss for the four possible HAP propagation environments at three different frequencies (2, 3.5, and 5.5 GHz) are given.

Berioli, Molinaro, Morosi, & Scalise (2011) discussed the current trends and the most recent advancements in the utilization of aerospace communications for emergency rescue applications. The authors give an overview of the public safety communications scenarios and of the state-of-the-art developments in the field. The paper continues by introducing the architectural approaches exploiting aerospace communication infrastructure in the provision of emergency communications services. Issues with the size of terminals that are used in conjunction with the satellite system were discussed. An interesting aspect of the paper was the focus on the integration of the aerospace segment with terrestrial backbones and ad hoc terrestrial networks for both data connections and assisted localization. The systems and solutions proposed are complex in their nature and more closely resemble a full communications system. This system is more complex than the system envisaged in this dissertation.

Buchter, Reinhold, Stenz, & Sizmann (2012) proposed using HAPs to extend broadband connectivity for aircraft. Three key elements of future ACNs, as discussed by the authors, were photonic high capacity communication links, hybrid photonic / radio-frequency diversity networking, and HAPs for permanent ACN-to-internet connectivity. The authors examined using lasers to communicate with the HAPs, but current laser technology is not suitable for this purpose, as the signal loss due to atmospheric conditions is very high. In the paper, the aircraft is acting as the sink for communications connectivity rather than a source, except in the case where an aircraft is acting as a communications relay for another aircraft. In the relay mode, a HAP could be substituted for a manned aircraft, and a mesh of HAPs could be used to form a communications network over the disaster zone.

Cellular Network Planning

Hurley (2002) examined the automatic location selection and modeling of cellular base stations. The research examined the design objectives of coverage, traffic capacity, and site financial cost. The research developed a framework for generating cellular network designs based on modeling. The designs are based on using multiple cell sites to serve the coverage area, but the principles involved can be used in this research where only a single cell site is considered.

Lee and Kang (2000) discuss cellular planning site location and site capacity as an integer linear programming problem. Their paper *Cell planning with capacity expansion in mobile communications: A tabu search approach* deals with AMPS and CDMA cellular systems, although the GSM system is mentioned briefly. The researchers use a tabu search to take a potential site location and check the results of the search with the location of the immediate neighbor locations in the hope of finding an improved solution.

Cell site location selection and the frequencies of use of the site have a mutual influence on each other and can be modeled as linear integer programs (Mathar and Schmeink, 2002). Their research paper *Integrated optimal cell site selection and frequency allocation for cellular radio networks* developed a linear program that maximizes the carried traffic by simultaneously selecting optimal locations for cell sites and their channel assignments. This methodology proved useful for this dissertation.

Channa & Ahmed (2010) presented a survey of emergency response communication frameworks and the potential security services required to provide reliable and secure information exchange during emergency situations. Normally in the immediate aftermath of a disaster, the traditional communication infrastructures such as landline or cellular networks are damaged. This damaged infrastructure often does not provide adequate communication services to first responders for exchanging emergency related information. There are privacy and security requirements for emergency response communications, including matters such as data integrity, authentication, key management, access control, and availability.

Reynaud, Rasheed, & Kandeepan (2012) outlined how an aerial telecommunications network can optimally meet the needs of emergency relief and recovery operations. They proposed a novel network architecture made of an integrated and multi-purpose aerial telecommunications infrastructure that could be extended with fast-deploying, high or low altitude platforms. Their research was theoretical in nature and provided a framework for the calculation of the voice and data traffic likely to be generated by emergency response teams in the wake of a disaster. The communication needs of the rescue teams in the wake of Hurricane Katrina were used as inputs to the traffic demand modeling for the airborne communications network.

Dovis, Fantini, Mondin, and Savi (2002) examined the derivation of a theoretical channel model for the communication link between the HAPs and terrestrial cellular terminals. The authors in particular examine the problem of modeling the effects of small-scale fading on the communications path. Small-scale fading occurs when the received signal experiences constructive and destructive interference over short periods of time and/or short geographical distances due to the relative motion of the transmitter and receiver. The authors developed a specific model applicable to the stratospheric channel using the particular geometry of the propagation scenario between the air and the ground. The paper does not deal with any specific communications system but looks at general signal loss of a radio frequency carrier.

There are emergency communications systems available in the market place today, and one such system was discussed in the paper *Integrated GSM/Wi-Fi backhauling over satellite: Flexible solution for emergency communications* (Frazil, Werner, Courville, Berioli, & Boussemart, 2008). This emergency communications system used a compact, ruggedized satellite terminal that could be used for communications in an emergency. The terminal provides GSM coverage in disaster areas where existing communication infrastructure is destroyed or overloaded. The system has a GSM base station and uses satellite to transport or backhaul GSM signaling and data traffic to the core GSM network infrastructure located away from the disaster area. Issues related to the terminal design and the tests undertaken were presented in the paper. The system is not a standalone system, and the coverage of the system was limited, as the base station still will need a tower or high building for the cellular antenna to provide adequate area coverage. The airborne, self-contained communications system, as envisaged in this dissertation, would negate both of these issues.

In order to justify why an emergency communications system is needed, Eriksson (2010) conducted a qualitative study using focus groups to examine various uses of cellular telephony. The research was carried out in Sweden, a country with a very high penetration of cellular phones. In Sweden, cell phones have become ubiquitous, and the paper concludes citizen cellular telephony use places great demands on the *public safety answering point (PSAP)*. PSAPs are the 112/999/911 emergency service telephone operators. Consumer expectations are dominated by increased necessity for trustworthy and helpful interaction with PSAP operators. The study further reinforces the notion people expect their cellular phones to work at all times, no matter the situation and is useful as a basis for why this subject matter is important.

Al-Hourani, Kandeepan, and Jamalipour (2014) developed a theoretical propagation model for the path loss of a low-altitude platform in an urban environment. The model will be of interest as a basis to predict the air-to-ground coverage of the system envisaged in the dissertation. The authors did not physically verify the model; the model only relates to outdoor coverage, and the effects of building loss with indoor propagation are not considered.

The critical nature of the elevation angle is such that HAP performance becomes degraded if the angle between the terminal on the ground and HAP exceeds 60 degrees (Iskandar & Kurniawan, 2011). The researchers evaluated the impact of elevation and azimuth angles variation, building height, and the size of the street where the cellular terminals were located that received the signal from HAPs. In order to examine the propagation loss experienced by this system in urban areas, the authors developed the building-block model and the ray-tracing tool for simulation. As a result, propagation loss as a function of elevation and azimuth angles was obtained. The results obtained were compared to the result of a physical-statistical model. The different scenarios clearly show the critical limitations of cellular communication when using a HAP.

When considering capacity planning for an ACN, one of the major issues with any cellular communications system is the deterioration of performance in the urban environment due to the extra loading of traffic on the system because of the increase in the number of likely users (Taha-Ahmed & Calvo-Ramon, 2009). The authors' research examined the performance of the downlink communication between the base station and user and the performance of the 3G UMTS standard in the context of a HAP environment. The modeling of the technology in the paper give good insight as to the theoretical performance of such a system in a real-world environment. UMTS technology, while superior in performance to the GSM system, is not as simple and robust as the earlier generation of cellular technology. The research methodology provides a suitable framework for the conduct of this research.

System modeling is important to gauge how useful any ACN will be in the event of a disaster. Camara et al. (2009) looked at the degradation of communication network performance in the aftermath of an earthquake, a flood, a major power outage, and a random major network failure. The research is useful as it presents realistic test scenarios that could equally be applied to an ACN based network. This research concentrates on a network of multiple nodes. This dissertation examines a single node network only in order to keep the limit the scope.

For an ACN platform, three main vehicles were proposed for hosting the communications system: unmanned airships, unmanned aircraft, and manned aircraft (Elabdin, Elshaikh, Islam, Ismail, & Khalifa, 2006). Each platform has certain advantages, but the purpose of this research is not to compare the full merits of each. The advantage of an *airborne platform (AP)* in comparison to traditional terrestrial or satellite-based systems is that the AP has a relatively low cost of procurement and operation compared to a multi-site terrestrial network or a communications satellite. When the ACN needs to be moved to a different location or brought back to earth for upgrading or redeployment, this also is possible. As an ACN operates at a much higher altitude than a cell site, the potential coverage footprint is much larger than transmitting equipment mounted on a tower.

The regulatory environment governing the operation of UAVs is still developing. The Federal Aviation Administration (FAA) in the U.S. is in the process of developing some formal rules and regulations. The FAA has stated that the commercial use of drones is unlawful (Frenzel, 2014). The FAA has indicated that recreational use of drones is permitted except that users must stay at least five miles away from an airport or report flights to the airport and keep the drone flying below 400 feet and within sight (Frenzel, 2014).

GSM SMS message is a short 160-character text communication that can be sent via a GSM cellular network (Agarwal, Chandran-Wadia, & Apte, n.d.). SMS offers two types of service. The first method is a point-to-point service where individual cellular subscribers send and receive messages from their cellular phones. The second, not so commonly used method, known as cell broadcast, is where all the cellular subscribers in the cell receive a common message sent from the cellular network itself (Agarwal et al., n.d.). Research by Agarwal et al. (n.d.) resulted in the construction of a model for the probability of an SMS message being refused or blocked by the network based on the arrival rate of the SMS, the time taken to service each SMS, and the number of resources or channels available to process the SMS.

The Dutch government has trialed an emergency alert system using cell broadcast that uses GSM technology to send messages to cell phone users in a particular area (Clothier, 2005). If a disaster occurs, a broadcast message is sent to all phones in that area warning of the danger and providing basic information. The Dutch interior ministry spokesman Frank van Beers, when asked about the advantages of cell broadcast, said, "This is a more instantaneous way of informing people about what is going on right now. It's an extra medium to communicate directly with people during a disaster" (Clothier, 2005).

One key concept of the system in this dissertation is the ability of the communications system to buffer or store a message in the case where the intended recipient is not in range of the system. Frew & Brown (2008) discussed this concept of buffering messages and gave it the name of data ferrying. In the event that the communication message between the sender and the recipient is not successfully delivered when first sent, the system can store the message and either retry to transmit the message at a specified time interval or when the recipient re-registers on the network. This ability to buffer is an ideal feature of the SMS standard, particularly applicable in the situation where the airborne platform is orbiting, and not all users will receive coverage at the same time. The ability of the system to store and forward an SMS message is a crucial element of the system design in this dissertation.

The store and forward nature of the SMS system is an effective approach for communicating during emergency situations and in environments not having continuous network connectivity (Jiang & Bigham, 2011). In a delay tolerant network, such as SMS, there does not need to be a continuous connection between the sender and the receiver for the communication to be successful. Jiang & Bigham (2011) carried out research on the performance of a messaging system, not dissimilar to SMS, but IP based, in a series of emergency scenarios, and showed the probabilities of successful message delivery given the number of user densities.

Short messages, as they require fewer network resources compared to a voice call, are an ideal way of communicating during disasters. Each GSM voice channel can be subdivided to allow the sending or receiving of eight simultaneous SMS messages. During natural disasters or other events that cause the voice traffic to spike, SMS is a more efficient method of communications. Indeed, John Britton, an AT&T spokesman said, "If you're on a wireless network and you can't get a call through, often the texting network won't be as congested" (Kawamoto, 2008).

Network Modeling

A model is not a precise reflection of reality; it is just an idealized representation of what is being studied. Thus, a model is used to simplify complex realities to an understandable and manageable form (Jin, n.d.). Figure 3 depicts the levels of abstraction that characterize the development of a model. The assumed real world is abstracted from the real situation by concentrating on the important variables that control the behavior of the real system. The model expresses, in an amenable manner, the mathematical functions that represent the behavior of the assumed real world (Taha, 2007). The model will be important to properly refine the deliverables of the project and to predict the system performance.

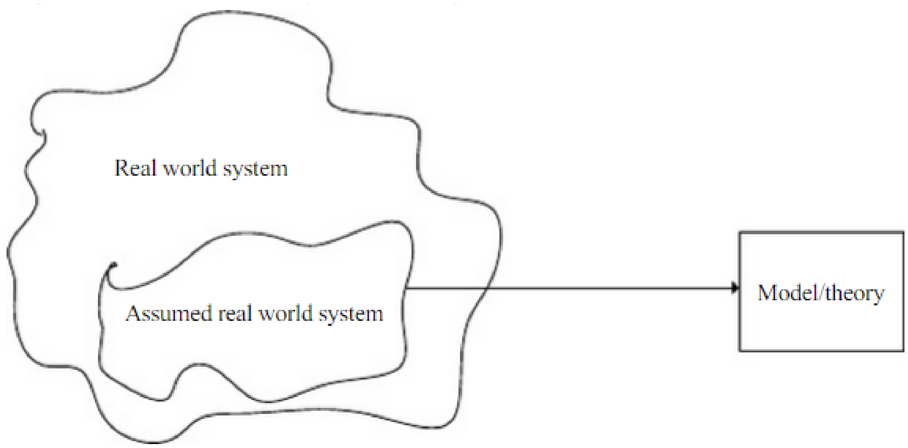

Figure 3. Model theory and reality. Diagram outlining difference between model theory and reality. Adapted from “Operations research: An introduction (8th ed.)”, by H. A. Taha, 2007, Upper Saddle River, N.J: Pearson/Prentice Hall.

In order to model the communications system, the different stages of sending a SMS need to be modeled. SMS message setup takes 235 milliseconds as does the return acknowledgement (FCC, n.d.). The data throughput of a Standalone Dedicated Control Channel (SDCCH) used for SMS is 98 bytes per second, equaling 9 milliseconds for every SMS character (FCC, n.d.) For an SMS message of 160 characters, the SMS transmission time is 160 x 9 = 1440 milliseconds per SMS message (FCC, n.d.). Table 1 summarizes the calculations on the time to send an SMS message.

Table 1

Total Time to Send an SMS message

SMS setup in ms	235
SMS transmission time in ms	1440
SMS return ack. in ms	235
Total SMS transmit time in ms	1920
Total SMS transmit time in seconds	1.92

SMS point-to-point message is successful because of its simplicity as a personal messaging service. Mobile users carry their phones with them all the time and are normally able to send short messages wherever and whenever they want. SMS is the ideal messaging service for short notice. An SMS message normally reaches the recipient wherever they are, and it transfers the information as soon as possible. In the event that the recipient's phone is switched off or outside radio coverage of a network, then the short message is normally received as soon as the phone re-attaches to the network (Trosby, 2010, p. 131). There has been work on the use of SMS to send user location data. The Industrial Technology Research Institute (ITRI) of Taiwan has developed an open standard for using SMS to exchange location-based information (Torres, 2013). The standard, called Open GeoSMS, has been effective in facilitating humanitarian coordination and disaster relief. This standard allows location data to be transmitted even if the transmitting or receiving device does not have internet access. Many cellular phone devices contain pre-installed maps and a *Global Position System (GPS)* receiver and can use these data sources in the absence of a cellular data connection (GeoSMS, 2010). The Android/iPhone application *Here I am 2*, can send an SMS message containing the user's co-coordinates (Code Selector, 2010). If this application was pre-installed on users' phones before a disaster, in the event of an emergency a user with a suitable phone could send its location via the ACN to a third party via SMS.

The process by which a cellular phone user is initially allowed onto a GSM network is referred to as *registration* (Jalihal et al, 2014). Normally the subscriber is registered in a database referred to as the *Home Location Register (HLR).* This data could be preloaded on the network-in-a-box in advance of the disaster. There is another option called auto registration that would be applicable in the instance that the cellular user was not previously on the network (Jalihal et al, 2014). Here the system allows a user to log on to the network and then select a phone number they wish to use. Another novel, post-disaster communications service discussed by Jalihal (2014) was the *I am alive* service, where the user can send an SMS message to a central number, and the message is stored in a database that is published and available for public viewing online.

The literature review has reinforced the assertion that natural disasters can cause serious damage to communications infrastructure. Various communications systems have been examined, and research into the feasibility of using UAVs for communications has been discussed. Gaps in this research have been highlighted showing that studies examined fall short in some respects such as a lack of field tests or experimental validation of using UAVs. There are gaps in the existing body of knowledge in that a model of an Airborne Communications Platform (ACP) has not been developed before, and implementing a test system based on this model has not been completed.

CHAPTER III

METHODOLOGY

This research was developed from the theory examined in the literature review introduced in Chapter 2 and combined with the research aims of Chapter 1. This chapter reviews the methodology utilized to analyze the modeling of a UAS for the purpose of providing post-disaster communications.

In order to solve the research question on page 7 in Chapter 1, the steps should be considered as per figure 4, beginning with the definition of the problem as part of the problem statement. The research involved an iterative process to design a working Airborne Communications System. The system was modeled mathematically and then experiments carried out to verify the system performance. A comparison between the theoretical and experimental results was carried out and the results examined.

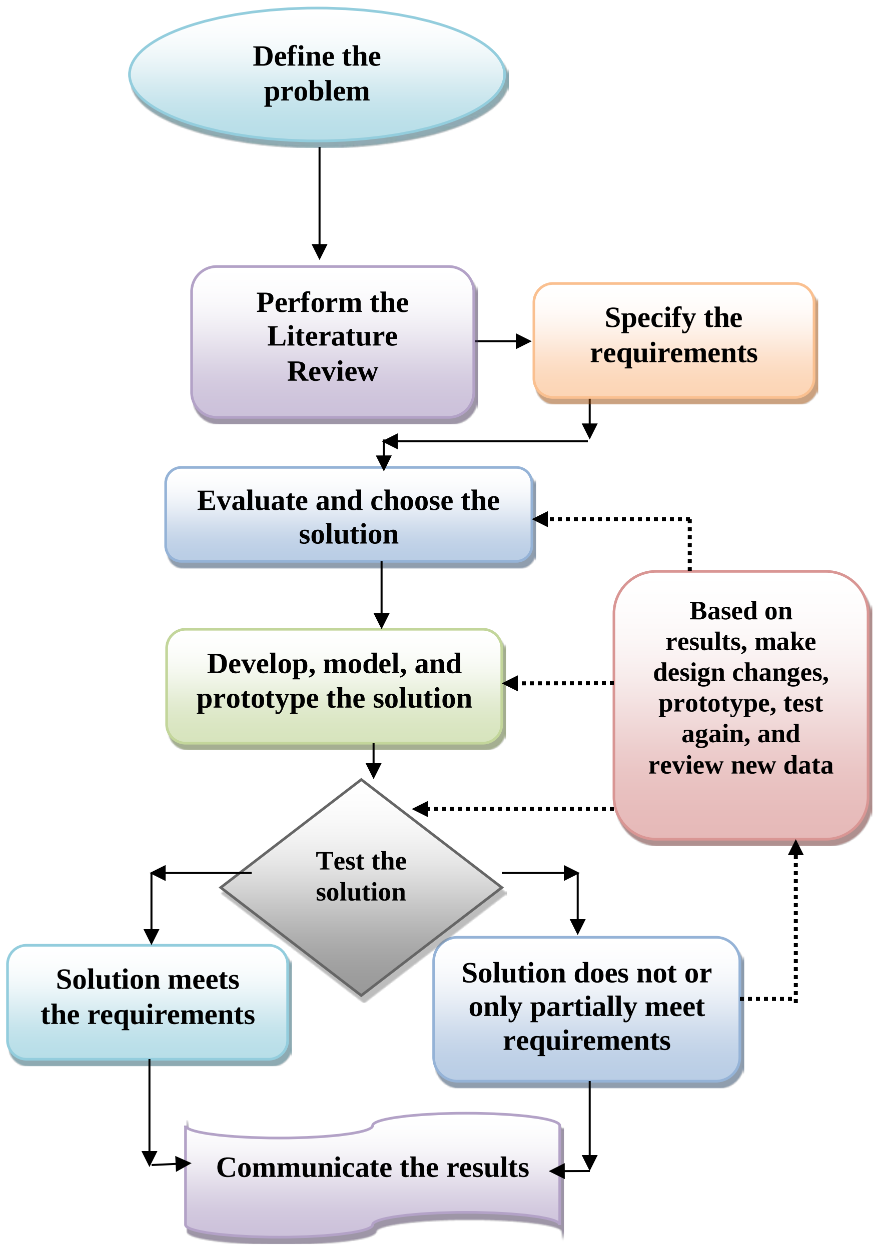

Figure 4. Research design process.

The literature review has provided the background research. The system requirements were discussed leading to the next stage of the planned research where a range of possible solutions were examined. The best solution was selected based on the earlier predefined criteria. The system was modeled, and a test system built. The system was tested and redesigned when necessary to meet the requirements.

Airborne communications systems have the advantage over terrestrial systems in that they are quick to deploy and can be moved and re-used between locations. In a region such as the Caribbean, moving equipment and spare parts among countries in the wake of a disaster can be challenging as port and airport facilities could be damaged. The volume of emergency relief supplies swamping the transportation systems may also cause delays with delivery. An airborne system such as the system proposed in this research could fly into the disaster-hit region at very short notice and be up and running very quickly.

This combination of the communications equipment and a UAV is defined as an Unmanned Air System (UAS). Evaluating the performance of this type of UAS is an important step in order to predict possible problems that can affect the system in a real environment. The behavior of a communications system in a scenario where the base station is moving is relatively new in the field of cellular communications.

Terrestrial cellular systems cannot physically move to adjust for changing coverage or traffic demands. In this research, the cellular network is modeled as moving above a particular region in order to provide emergency communications. The UAVs orbit and flight path can be altered based on the requirements of the communications system. For example, the altitude of operation of the UAV can be altered to expand or reduce the radio coverage area. The velocity of the UAV can similarly be altered to adjust the amount of time the communications system provides cellular coverage in a specific area.

In order to predict communication problems that may affect the UAS performance, the entire system was evaluated using modeling under a realistic test environment. It is important to use a realistic mobility model, as the node mobility has a great effect on the network performance and the communication radio performance.

As discussed in the literature review, theoretical studies have shown that an ACN has many advantages in a disaster scenario, but no deployment model or trial of a complete civilian system has occurred. This research encompasses the theoretical design and modeling of an ACN and involve trials to show the performance of the system in a demonstration of the solution.

The research question defined the problem to be solved, namely, can an airborne emergency wireless communications system be modeled to provide design guidance on cellular communications service for use in disaster-aftermath related scenarios? The literature review discussed the existing research and gave a background overview of research in the area.

System requirements and performance assumptions will be defined in terms of the number of users of the system, what services will be offered to these users, and the specific emergency scenario with which the system is designed to cope. The specific-use case is a defined geographic area with a relatively fixed population, in order to keep the scope of the research defined, focused, and manageable. The overall goal is to model a fully operational ACP system capable of serving up to 125,000 subscribers. Table 2 shows the population and mobile phone penetration of a selection of Caribbean and Pacific islands and the average of the group. The average population is 125,000 of a sample of Pacific and Caribbean islands. It is possible to have more that 100%

penetration in circumstances where a person has two cell phones. If everyone in the country had a phone but in addition one person in four has two cell phones than the penetration is 125%. This statistic does not imply that everyone has a cell phone it just shows the ratio of cell phones to people in the particular country.

Table 2

Population and Cellular Penetration of a Sample of Pacific and Caribbean Islands

Market	Estimated population in thousands	Estimated Cellular penetration in %
Anguilla	16	182
Antigua and Barbuda	91	127
Aruba	111	135
Barbados	290	108
Bermuda	70	144
Bonaire	18	189
British Virgin Islands	33	188
Cayman Islands	55	168
Curacao	147	128
Dominica	73	130
Grenada	110	126
Guadeloupe	406	158
Martinique	386	152
Montserrat	5	88
Nauru	9	86
Samoa	197	124
St. Kitts and Nevis	52	142
St. Lucia	163	116
St. Vincent and the Grenadines	103	115
Tonga	106	55
Turks and Caicos	49	114
Vanuatu	267	50
Average	125	128

Note. Data from Digicel SEC filling 2015. Adapted from information for each of the markets in the Caribbean and South Pacific. Retrieved from http://www.sec.gov/Archives/edgar/data/1645826/000119312515236163/d946689df1.htm#rom946689_8

The thinking behind the research was to keep the functionality of the system as simple as possible. A state-of-the-art wireless communications network would allow data connectivity and connections to users outside the network. This would require a link to the terrestrial network and add enormously to the overall system complexity. A more complex network would deviate away from the core principle that the timely provision of some communications, no matter how limited, is better than no communications at all. The system should not need any interface or connection with the terrestrial-based communications network and should only facilitate text communications point-to-point between users registered on the network.

The next stage of the research was to develop a technical solution and subsequent system model to satisfy the research requirements. The evaluation and validation of the model for the staging and placement of the ACN in a specific environment is a continuation of the work of Bartolacci et al. (2013). The model is based on a specific case presentation, based on the previous criteria problem scenario that could be expected to be repeated in most similar subsequent disaster incidents. The case could be a scenario as happened in a previous disaster where major network elements were destroyed.

For example, following Hurricane Ivan in Grenada in 2005, the key microwave link site for all communications traffic of the largest cellular operator off the island was destroyed by high winds. The fiber optic sub-sea landing station was damaged rendering the island isolated from a telecommunications perspective. The research strategy for this stage is to devise a system model to adequately model the ACN, considering factors such as the system capacity and preferred deployment location. No public research exists to show how the use of an ACN can be optimized from a logistics and cost point of view

(Bartolacci, 2014).

The fourth stage of the research was to implement the system as defined by the model, through the modeling of a pilot system on a limited-scope application. There are several key technical issues to be addressed at this stage of the research. The first issue was how the ACN controls initial access to the system from users on the ground. The GSM system works by allowing registered users to access the system and also excludes non-eligible users from access. The process whereby a user is deemed eligible is part of the registration and authentication procedure when a user's terminal first tries to access the network. The emergency system has to have a special admission control policy to allow a suitable user to log on the system.

The next technical issue to be addressed was how the network will deal with the overload and congestion problems that may arise if too many users try to access the system at the same time. Limiting the network coverage can reduce the number of users accessing the network, and techniques to implement this limitation will have to be examined.

The fifth stage of the research was to evaluate the system performance through an actual demonstration of the test system to ensure the original system requirements are satisfied. This required multiple iterations of testing, beginning with a relatively simple series of experiments growing in complexity with each additional iteration of the experiments. The first experiment was to get the network-in-a-box operational in a laboratory environment, with one sending phone and one receiving phone. The next stage was to repeat this experiment with multiple phones. Subsequently, the experiment was sending multiple SMS messages per phone over a time period and measuring how the system performs compared to the model. The next iteration of the trial was to repeat the experiment outdoors with the network-in-a-box in a fixed elevated location.

A typical test network-in-a-box is supplied by Range Networks and is shown in Figure 4. The equipment is a fully self-contained GSM network with all the necessary component modules to allow the sending and receiving of SMS messages.

Figure 4. Network Kickstarter Kit. Example complete cellular network in a box. Reprinted from Range Networks Network Kickstarter Kit description. Reprinted with permission.

In order to simulate multiple cellular users, a multiport SMS modem was used. Figure 5 shows a sixteen-card SMS modem bank. This unit is a bank of 16 GSM terminals that can be individually programmed via script running on a laptop to send or receive SMS messages. Two such devices were used where the first is used to simulate the sending parties. A second bank was used to simulate the receiving parties.

Figure 5. 16 Port SMS Modem. Photograph of a multi-unit SMS device. Reprinted from product description of 16 port 3G SMS MODEM POOL, 2015. Retrieved from http://www.chinaskylinetelecom.com/path012/201504/16port3GSMSMODEMPOOL24180623/. Reproduced with permission.

The number of subscribers assumed in the modeling of the ACN was 125,000. The communications service selected for the system is point-to-point SMS and cell broadcast messaging. A text-based SMS messaging system has been selected as the best method to provide the emergency point-to-point communications for the reasons discussed in Chapter 2.

The use case considered is the complete failure of the terrestrial cellular network on a Caribbean island. The occurrence of this event does have a historical precedent, in that the Digicel network in Grenada was completely off-air in the wake of Hurricane Ivan in 2004. Using this island as an example application is a real-world example of a specific geographical area that could have limited communications services restored through the deployment of the ACN.

To facilitate communications in the area affected by the failure of the terrestrial cellular network, an ACN would be deployed. The ACN uses GSM technology, as this is the most widespread technology employed in the world today, and for the additional reasons outlined in the earlier chapters. The ACN is configured to facilitate SMS messages to allow as many messages to be transmitted as possible.

The elements of the network-in-a-box do have a finite ability or capacity to process messages. If a message cannot be processed immediately by the system, then it is either be rejected or queued. Queuing theory is the discipline of mathematics that examines the process of waiting. The science of queuing theory began when Agner Erlang began to examine congestion problems raised by the processing of phone calls in a telephone exchange at the beginning of the 20th century (Sztrik, 2012, p.11). Queuing theory is a field of applied probability theory, and queuing problems are examined using probabilistic methods. One example of a queue is a line of customers in front of the service window at a post office. Another example is a group of passengers waiting to have their travel documents examined at passport control. The number of customers in the line grows and shrinks with time, and the waiting time can be unpredictable. Given that the number of customers in line is a random variable that changes with time, the system of customers and servers fits the definition of a stochastic or unpredictable process (Jensen, 2004). The input to the model is subject to uncertainty and is described by a probability distribution.

A queue results when demand for service temporarily exceeds the capacity of the service facility (i.e., whenever a customer or text message arriving cannot receive immediate attention because all servers are busy). This situation is almost always guaranteed to occur at some time in any system that has probabilistic arrival and service patterns. It is not normally possible to increase service capacity beyond a certain point, due to the expense involved or because of system constraints. If the cost of expanding the serving capacity were no object, then theoretically enough servers could be supplied to handle all arriving customers without delay. A limitation in this maximum service capacity can cause an increase in the time the customer must wait to be served. The objective of queuing models is to examine levels of service based on the number of customers versus number of servers.

The Erlang B and Erlang C models may appear complex at first, but they are relatively easy to implement using a program such as Microsoft Excel. In order to model the system, the input parameters need to be established and the selected values explained. In the first iteration of the system, the model considered is for a network-in-a-box, using a single BTS with a single Transmitter Receiver Module (TRX). The TRX is the part of the BTS that handles the encoding, encrypting, multiplexing, modulating, and transmission of signals to the antenna (Tutorialpoint, 2016). The TRX also performs the reverse action in the receive path of decoding, decrypting, and equalizing received signals. A TRX is assigned a GSM channel of 200 KHz in size. This channel is subdivided into eight Time Division Multiple Access (TDMA) timeslots. Each of these time slots allows one simultaneous voice call. As previously discussed, however, each voice channel can be further subdivided into eight signaling channels. Of these 64 sub channels, one has to be reserved as a beacon channel, allowing 63 sub channels to be used to carry SMS traffic (ECE, n.d.).

The Airborne Communications Network is modeled as hosting a GSM network-in-a-box with the parameters as per Table 2. In a cellular network, not every possible subscriber is attached or actually connected to the network at the same time. The typical value of attached versus registered customers is 75% (P. Singh, personal communications, April 29, 2016). A cellular subscriber sends in the region of 250 SMS messages per month (Evans, 2015). The number of SMS messages per month can be converted into SMS per second by first dividing the monthly total by the number of days in the month. A month is assumed to have an average of 30 days. The busiest hour of the day for traffic is assumed to carry 10% of the total traffic for the day (P. Singh, personal communications, April 29, 2016). From the number of busy hour SMS per customer, the number of SMS per second can be further calculated.

An SMS message can be up to 160 characters in length (FCC, n.d.). The average length of an SMS message is 51 characters (Battestini, Setlur, & Sohn, 2010). The number of characters in the SMS affects the transmission time of the message. In theory, a 51-character SMS takes 0.929 seconds to transmit from the MS to the BTS over the Standalone Dedicated Control Channels (SDCCH). The SDCCH are used to provide reliable connection for signaling and SMS in the GSM system. The number of system SMS messages per second is calculated by multiplying the average SMS per second per user by the total number of attached subscribers. As only 75% of subscribers are active according to the assumptions, if a person sends an SMS message to another person on the network, there is a 25% chance the other user is not active, and therefore the message will have to be stored.

Table 3

System Inputs for Modeling of ACN

System Inputs	Suggested value	Range of values
Number of subscribers	125000	0 to 1250000
Number of attached subscribers	93750	0 to 93750
Number of messages per subscriber per second	0.0002306	0 to 0.002778
Percentage blocking	3	0 to 100
Number of GSM/SDCCH timeslots	63	0 to 63
Average SMS message length in characters	51	0 to 160
SMS message of average length time to transmit in seconds	0.929	0.47 to 1.92
Number of SMS per second Mobile originated	21.61	
Number of SMS per second Mobile terminated	16.21	
Total Number of SMS per second	37.83	

For a BSS network, the system is modeled for varying values of SMS per second. By varying the system input parameters, the number of system SMS per second can be changed. The modeling shows sensitivity analysis of how varying the input parameters affects the system performance. *Performance* is defined as the ability of the system to successfully process all the SMS traffic offered it. By using the Erlang B formula, assuming 63 resources (channels) to process the SMS in the BSS portion of the network for 38 SMS per second, the chance of successfully sending the SMS is 100%. If the traffic is doubled to 80 SMS per second, the success rate is 75%, meaning 1 attempt in 4 to send an SMS would fail. With a tenfold increase in SMS traffic, the chance of successful SMS transmission drops to 16%.

Table 4

Blocking and Success Percentage for SMS Transmission Assuming 63 Resources

Number of SMS	Prob. Blocking	Prob. of Success
1	0.0%	100.0%
5	0.0%	100.0%
10	0.0%	100.0%
20	0.0%	100.0%
30	0.0%	100.0%
38	0.0%	100.0%
40	0.0%	100.0%
50	1.1%	98.9%
60	6.9%	93.1%
63	9.4%	90.6%
70	15.8%	84.2%
80	24.6%	75.4%
90	32.2%	67.8%
100	38.5%	61.5%
110	43.8%	56.2%
120	48.4%	51.6%
124	50.0%	50.0%
150	58.5%	41.5%
200	68.7%	31.3%
250	74.9%	25.1%
300	79.1%	20.9%
400	84.3%	15.7%
500	87.4%	12.6%

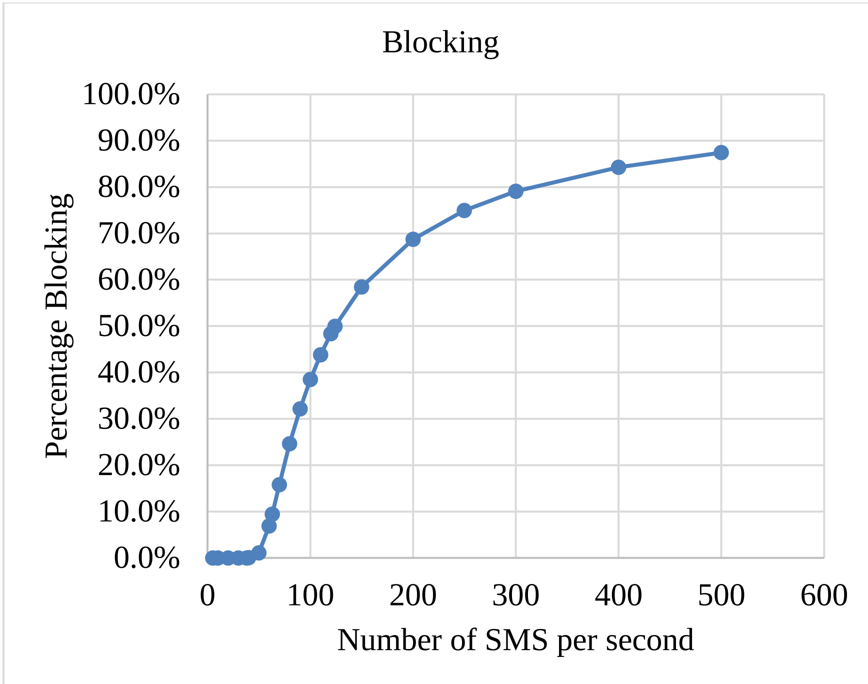

Figure 7. Blocking rate of SMS transmission in BSS assuming 63 resources.

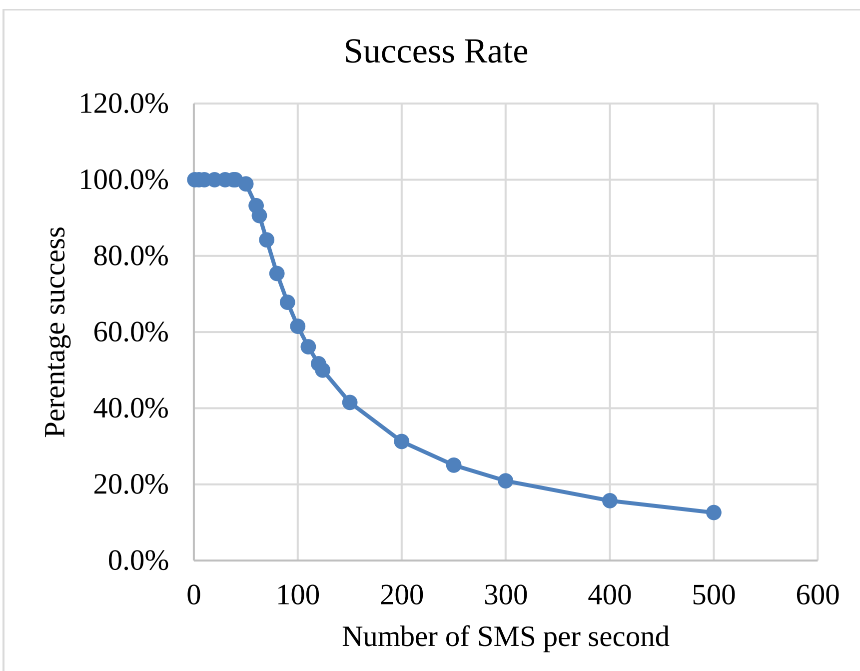

Figure 8. Success rate of SMS transmission in BSS assuming 63 resources.

For an NSS network, the system is modeled for varying values of SMS messages per second. However, in this case there is a limit to the number of SMS messages passing from the BSS network to the SMS-C in the NSS. There are only 63 resources that can handle the SMS messages in the BTS. Therefore, the maximum number of simultaneous SMS messages that can be sent to the SMS-C is limited to 63. The SMS-C is considered as a single server, but it can process the SMS messages much more rapidly than the TRX. An SMS-C, used by a telecommunications operator can typically handle 100 messages per second (P. Singh, personal communications, April 29, 2016). The SMS-C will not block the incoming SMS messages, in the event that it becomes congested. The SMS-C will buffer both incoming SMS messages, until they can be processed, and outgoing SMS, until they can be terminated. The modeling shows a sensitivity analysis of how varying the input parameters affects the system performance. *Performance* is defined as the ability of the system to successfully process all the SMS traffic offered to it. By using the Erlang C formula and considering the SMS-C as one server that works at a service rate of 0.01 seconds per SMS (100 SMS per second), for a maximum of 63 SMS per second, the probability of successfully sending the SMS is 100%. This is because the arrival rate of 63 SMS messages per second is well within the message handling capacity of the SMS-C. The SMS message is delayed, but the time of the delay is 0.027 seconds, at a rate of 63 SMS per second.

Table 5

SMS-C System Performance

Service rate	Arrival rate of SMS	Erlang	Erlang C	Average buffer length	Average queuing time (S)	Average queue length	Average delay (S)
0.01	1	0.01	1%	0.00	0.000	0.010	0.010
0.01	5	0.05	5%	0.00	0.001	0.053	0.011
0.01	10	0.1	10%	0.01	0.001	0.111	0.011
0.01	21	0.21	21%	0.06	0.003	0.266	0.013
0.01	30	0.3	30%	0.13	0.004	0.429	0.014
0.01	42	0.42	42%	0.30	0.007	0.724	0.017
0.01	50	0.5	50%	0.50	0.010	1.000	0.020
0.01	60	0.6	60%	0.90	0.015	1.500	0.025
0.01	63	0.63	63%	1.07	0.017	1.703	0.027
0.01	70	0.7	70%	1.63	0.023	2.333	0.033
0.01	80	0.8	80%	3.20	0.040	4.000	0.050

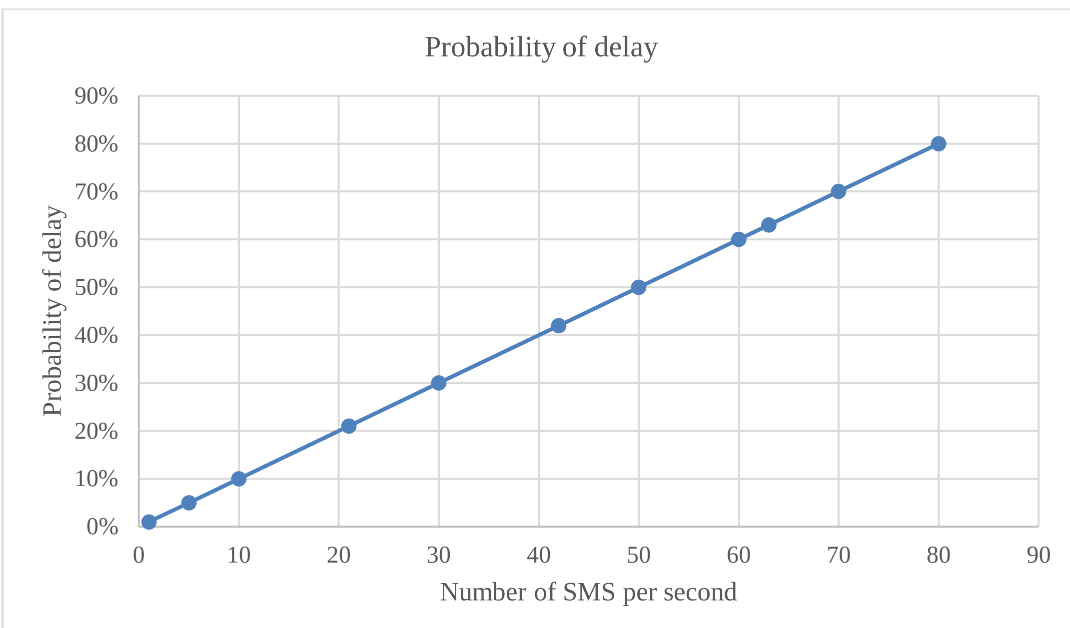

Figure 9. Probability SMS will be delayed in SMS-C.

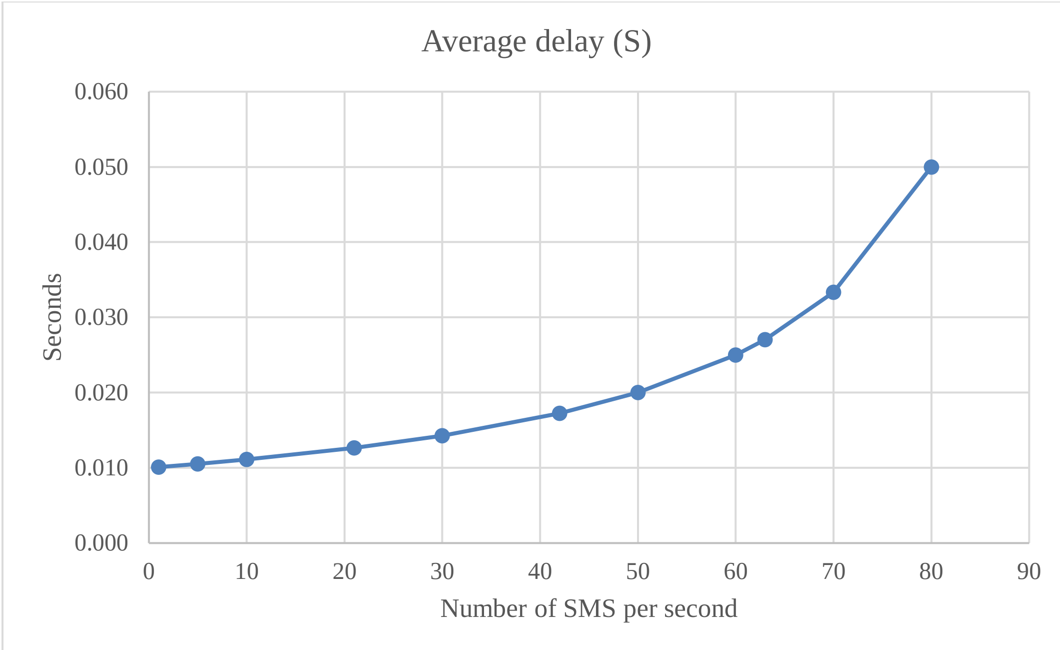

Figure 10. Average time SMS will be delayed in SMS-C.

Another feature of the GSM system is the ability to send a message from a cell site to every user attached to the cell site (or multiple sites) though a feature called *Cell Broadcast* (CB). CB is a GSM software feature that allows messages, of up to 15 linked messages each with up to 93 characters, to be broadcast to all cellular handsets and similar devices within a designated geographical area (Cell Broadcast Forum, n.d.). Cell Broadcast is designed for simultaneous delivery of messages to multiple users in a specified area; whereas, the SMS is a one-to-one and one-to-a-few service, Cell Broadcast is a one-to-many, geographically focused service. Regardless of network state (congested or not), CB is always available. Cell broadcast, in contrast to SMS, is part of the so-called *low-level* signaling between handset and network. In the case of network congestion, it may be impossible to use regular voice and SMS services, and CB will remain fully functional. Cell broadcast messages can be preloaded on the ACN to give information such as temporary emergency numbers that can be used to send messages to the emergency services. If the cell broadcast feature is enabled, one of the SDCCH timeslots is converted to a Cell Broadcast channel, used expressly for the purpose of sending Cell Broadcast messages (S. Wright, personal communications, April 29, 2016). In terms of capacity, the system would be reduced from 63 to 62 available time slots.

Radio Network Modeling

The next stage of the system modeling is that of the system radio performance, in terms of the coverage that the airborne communication platform could provide. In order to present a sample coverage area, the island of Grenada was considered. Grenada is an island with a total area of 348 square km and a population of 107,000 people (United Nations, 2015). Grenada is a typical Caribbean island in terms of size, terrain, and population. Digicel, the largest cellular phone company in Grenada, has 74,000 subscribers out of a population of 107,000, for a market share of 68%. If the ACP was in operation over Grenada in the wake of a disaster, it would need to service 74,000 cellular users.

The calculation of a cell site coverage area is typically expressed in terms of a link budget. Signal power is diminished by geometric spreading of the wave front, commonly known as Free Space Loss (Butler, 2013). The power of the radio signal is spread over a wave front, the area of which increases as the distance from the transmitter increases, and thus, the power density diminishes. Using decibels (dB) to express the loss and using a generic frequency f, the equation for the Free Space Loss (Equation 4) is:

$$L_{fs} = 32.45 + 20 \log (D) + 20 \log (f) \quad (4)$$

Where L_{fs} is expressed in dB, D is in kilometers, and f is in MHz.

For the GSM system, the minimum threshold signal level or Mobile Station sensitivity is defined as being -104 dBmW (Ericsson, 2014). In order to achieve good outdoor coverage, a number of factors, namely signal loss due to Rayleigh fading, attenuation due to the user body, and normal fading loss have to be taken into account. Table 6 details the values of these factors.

Table 6

GSM Receive Sensitivity

MS Sensitivity, (MSSENS)	-104 dBm
Rayleigh Fading Margin, (MARGRF)	3 dB
Interference margin, (MARGIF)	2 dB
Body Loss, LB (900MHz)	3 dB
Outdoor Log-Normal Fading Margin, (MARGLNF-O)	4 dB
SSREQ = MSSENS + MARGRF + MARGIF + LB	-104 +3 +2 + 3 dB
SSREQ = -96 dBm	-96 dBm
SSOUTDOOR = SSREQ + MARGLNF =	-96 dBm+ 4 dB
SSOUTDOOR	-92 dBmW

The minimum outdoor signal strength is therefore calculated as -92 dBmW.

The path loss formula assumes no clutter loss, which is signal attenuation due to buildings and terrain, but with an airborne platform transmitting to an MS outside in the open, this clutter loss will be negligible. The formula also assumes there is line of sight between the transmitter and the receiver.

Cellular telecommunication is subject to multipath fading. There are a variety of reasons for this. The first is that the mobile station or user is likely to be moving, and as a result the path lengths of all the signals being received are changing. The second is that many objects around may also be moving. Automobiles and even people cause reflections that have a significant effect on the received signal. Accordingly, multipath fading has a major bearing on the performance of cellular telecommunications.

Path loss calculations for mobile phone signals are shown in table 7. For a frequency of 900 MHz, with a transmit power of 1 Watt/30dBmW, the maximum distance for the free space path loss is 12 kilometers.

Table 7

Pathloss Calculation

Distance km	12
Frequency MHz	900
Transmit (TX) power dBmW	30
Antenna Gain TX	0
Cable/connector loss dB	-1
Free space loss dB	-119.6
Antenna Gain Receive (RX) dB	0
Cable/connector loss dB	-1
Expected receive signal level dBmW	-91.6

The radiation pattern from an antenna mounted on the bottom of the fuselage of an aircraft is shown in Figure 11.

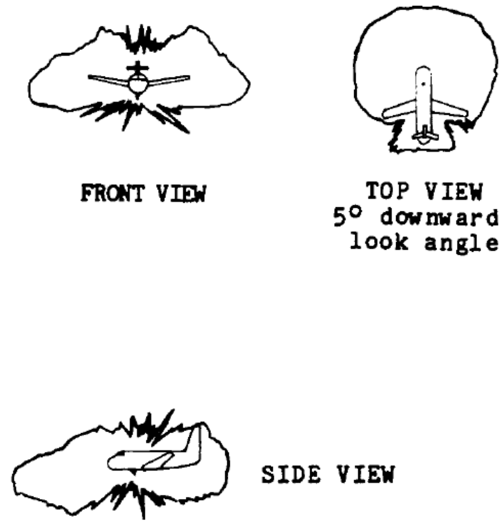

Figure 11. Radiation pattern of aircraft antenna (Child, 1985). Reprinted with permission.

The pattern from the top view can be assumed to be largely omni-directional with a bias toward the front of the aircraft. To calculate the distance a signal can travel from the ACP, Pythagoras' theorem can be used. Let R be the radius of Earth, and h is the altitude of the ACP. Line of sight distance (d) of this station is given by Pythagoras' theorem:

$$d^2=(R+h)^2 - R^2 = 2\,R(r + h^2) \qquad (5)$$

As the altitude of the station is much less than the radius of the Earth, d is approximately expressed as:

$$d \approx \sqrt{}\, 2\, R\, h \qquad (6)$$

If the height is given in meters, distance in kilometers (km). and taking the radius of the earth to be 6,370 km:

$$d \approx 3.57 \sqrt{h} \qquad (7)$$

At an altitude of 1,000 meters, the ACP has a line of sight distance of 113 km. As calculated earlier, the free space loss of the signal limits the effective coverage radius range to only 12 km. If the airborne platform is at an altitude of 1,000 meters, the cell radius on the ground can be derived from Pythagoras' theorem, where two sides are 1 km and 12 km and the remaining side is 11.95 km, rounded up to 12 km. So, the cell diameter, assuming perfect propagation, is 24 km. The island of Grenada is 34 km by 19 km, so a single ACP with a single cell or sector will not cover the entire island if the ACP maintains a small relatively fixed orbit (Grenada facts, 2015). However, with a racetrack pattern of length 10 km, this orbit pattern would ensure the entire island would, after the duration of an orbit, have enjoyed some coverage. The highest peak in Grenada is 840 m, so 1,000 m provides clearance of this terrain.

Verification and Validation of System Models

In order to have confidence that the modeling results are an accurate depiction of the real system, the model needs to be verified and validated (Anderson, 2008, p. 569). Verification is the process that determines that the mathematical calculations made are correct. For the modeling exercise, the communications theory formulas for Erlang and path loss are used. However, there are certain checks that can be used to verify the calculations. The Westbay Engineering online calculator is an example of a second calculation source used to check the first calculation results (Westbay Engineers Limited, 2014). The online calculator was asked to calculate the percentage of blocking given 63 resources / lines and an offered traffic of 63 Erlang. The result was a blocking rate of 9.4%, and this corresponds with the previously calculated value in Table 3.

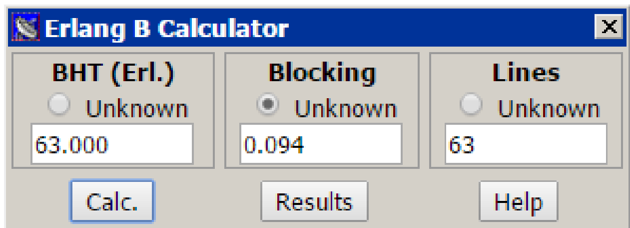

Figure 12. Screenshot of Westbay Erlang tool for Erlang B formula. Used with permission.

The Erlang C calculations were also verified using the same method. These tests gave a high confidence that the Excel calculations were error free. The theoretical model was therefore confirmed by using calculations derived from multiple sources.

Advantages of Modeling

The advantage of modeling is that it allows analysis of complex systems in a way that may be difficult to do analytically. Simulations provide the flexibility to describe systems without the required assumptions that may be required by mathematical models (Anderson, 2008, p. 569). Simulations can predict when the system can become unstable or unusable by projecting the system performance.

System Access and Congestion Control

In the literature review, the registration process by which a cellular phone user is initially admitted was discussed. In a terrestrial network, the subscribers' data is registered in a database referred to as the Home Location Register (HLR). This database could be preloaded on the network-in-a-box in advance of the disaster. Another option, called auto-registration, would be applicable in the instance that the cellular user was not previously on the network.

For the OpenBTS network, this auto-registration works as a staged process. First, the mobile station attempts a location-updating request to attach to the network. Even though the MS is not registered, the network is configured to accept the request. While the MS still has an open dedicated channel to OpenBTS, OpenBTS sends it the open registration welcome message to the MS. This message is configurable within the system software and can deliver a message such as, “Please respond to this message with your telephone number to receive service". The user responds to the text message with a telephone number. The response message is transferred from the MS to OpenBTS to SMS-C software function block where it is delivered to the register short code function. The register short code function updates the Subscriber Register to provision the new user. The register short code function generates an SMS message for the user delivered by SMS-C via the OpenBTS to the MS. The registration process can be further simplified by allowing open registration. OpenBTS can be configured to accept all MS for registration regardless of authentication or provisioning status.

The OpenBTS platform can automatically adjust its downlink power to limit messaging load and prevent congestion. By using this automatic-transmit power adjustment, the coverage area is reduced to a smaller service area, and the corresponding population of phones the network can serve is reduced. When too many cell phones make simultaneous access attempts to the BTS resulting in all the available channels being in use, the BTS can respond to the MS with an Immediate Assignment Reject message. This reject message carries a value that dictates how long the rejected MS must wait before making another access attempt. OpenBTS implements an exponential back-off algorithm that causes value of the back-off period to grow exponentially whenever channel exhaustion occurs.

To summarize the research methodology following the specification of the requirements, an initial assumption was made, the results modeled, a trial conducted, results analyzed, the model tuned, and the iterative process begun again. For example, the results of modeling a small system with capacity for 50 simultaneous users will lead to the development of a model for a larger system with 250 simultaneous users.

The last stage of the research explained and communicated the results of the investigation. Discovering the system limitations and finding ways to deal with all the likely problems such as overload and congestion will be an important part of the investigation. The research results analysis will discuss what worked and what did not. The analysis will also discuss approaches that seem promising to overcome problems encountered but that may not have been solved.

In conclusion, this dissertation has outlined how this research uses quantitative modeling techniques combined with qualitative narrative methods to examine the use of ACP for provision of disaster communications. Details of the research methodology that will be used have been provided together with a discussion of some of the key technical concerns. Airborne communications platforms have the potential to provide an important communications bridge in the period immediately following a natural disaster

Implementation of a Test System

A verification exercise was carried out to compare the results of modeling to that of a real system. This added the advantage of cross-referencing the research. By this, the theoretical model of the system was compared with a real-life system. For this research, the OpenBTS network-in-a-box was selected for the actual testing of the system model. The Range Networks OpenBTS-GSM Desktop Kit is intended for professional lab and research use. The OpenBTS network allows for the modeling of small GSM cellular networks. OpenBTS enables the implementation of cellular networks by substituting legacy telecoms protocols with Internet Protocol and flexible software architecture.

A complete OpenBTS installation comprises several distinct applications:

- The actual OpenBTS application, containing most of the GSM software stack.
- The transceiver that is the software radio modem and hardware control interface.
- The SMQueue that is the store-and-forward server for SMS text messaging.
- The Asterisk Voice over IP private branch exchange (PBX) or soft switch.
- The application managing the database of subscriber information.

The OpenBTS Development Kit runs the public release of OpenBTS, with source code included under a free software license referred to as an Affero General Public License v3. The network-in-a-box equipment is the size of a large laptop computer.

Operation of Network in Closed Lab Environment

The OpenBTS network-in-a-box was setup in an indoor environment and configured with four SDCCH channels used for the sending and receiving of text messages. The frequency band and channel of operation had to be selected in order to minimize the possible effect of external interference. The OpenBTS can be programmed to use any of four possible frequency bands. The 850, 900, 1,800 and 1,900 MHz band are all selectable as possible bands of operation (Poole, n.d.). These are the standard frequencies worldwide for the GSM system. The lower frequency bands of 850 and 900 MHz have the advantage that propagation of the radio signals in this band are more favorable. Formula 4 demonstrates that the path loss of a signal is related to 20 times the logarithm of the frequency in MHz. An 1800 MHz signal contributes a 6 dB greater loss than a 900 MHz signal in terms of free space path loss.

In Jamaica, where the experiments were conducted, the 850 MHz and 900 MHz bands are occupied by the licensed cellular operators CWC and Digicel. Spectrum for cellular communications is a valuable and scarce commodity, and finding unused and unoccupied spectrum presents a challenge. However, in Jamaica there is a guard band between the 850 allocation and the 900 allocation to minimize interference between the two spectrum bands. A guard band is a portion of spectrum deliberately left vacant in order to minimize interference between adjacent portions of spectrum. It is the equivalent to a buffer zone between bordering countries. This guard band is in place as the 850 MHz downlink spectrum is adjacent to the 900 MHz uplink spectrum. In order to prevent the higher powered 850 MHz downlink transmission swamping the weaker 900 MHz uplink transmissions, a two MHz guard band is in place between the two spectrum allocations. This guard band is unoccupied and is relatively free of interference, especially in an indoor environment.

One of the aircraft system antenna was re-tasked for use for this experiment. The DME antenna on the aircraft can also be used as an antenna in the GSM900 band. For this reason the 900 MHz band was selected as the frequency band for the trial.

The GSM900 band is further subdivided into 124 discrete 200 kHz channels. The OpenBTS unit is a single TRX unit, therefore a single fixed channel is used. The selection of this channel is important to try to minimize the effect of interference to the system. This channel is referred to as the Absolute Radio Frequency Channel Number (ARFCN). An ARFCN is a unique number given to each radio channel in GSM. The ARFCN can be used to calculate the exact frequency of the radio channel. Within the GSM900 band, ARFCN 1 to 124 are used (Telecom ABC, 2005).

The network-in-a-box has a command line interface that permits interrogation of system parameters. A laptop PC was used to connect via a terminal window to the network-in-a-box via Ethernet cable. The network-in-a-box software runs on the LINUX operating system. Once the OpenBTS software has been accessed, the command "noise" allows the current noise level of a specific channel to be evaluated, and the results obtained by running this command assist in setting the system parameters such as the frequency of operation or the transmitter power setting, to minimize the noise. A scan of the available 900 MHz spectrum is displayed in Table 8. The scan was performed firstly with an indoor whip antenna, and then an external shark fin antenna was connected to the system to evaluate the background noise level in an outdoor environment.

Table 8

Result of Checking GSM900 Band for Background Noise Levels

ARFCN	Indoor signal level (dBm)	Outdoor signal level(dBm)
1	-60	-51
5	-59	-52
8	-63	-55
10	-58	-49
20	-58	-49
30	-58	-49
40	-54	-46
50	-49	-40
60	-53	-42
70	-54	-43
80	-55	-43
90	-54	-46
100	-58	-47
110	-51	-44
120	-57	-46
124	-57	-47

Digicel has been allocated the spectrum with the ARFCN 10 to 60. The ARFCNs in the block 61 to 124 are allocated as a license free Industrial Scientific and Medical band in Jamaica. Devices such as cordless phones and garage door openers typically operate within this band. The ARFCN in the range 1 to 9 are in the guard band between the 850 MHz allocation and the allocated portion of the 900 MHz band. These channels are less prone to interference than the other portions of the 900MHz band. ARFCN channel 8 was selected as the frequency for the OpenBTS to operate, as this was judged to be the channel with the least external interference.

In order to test the system in an outdoor environment, the test network needed additional hardware. The antenna arrangement on the indoor test system has separate transmit (TX) and receive (RX) antenna. In order not to have two separate antennas for this part of the testing, a diplexor that combines the receive signal and the transmit signal is required. This diplexor allows transmit and receive signals to be combined but prevents the much stronger transmit signal from entering into the receive signal path. The transmit signal has the potential to saturate the receiver signal chain adding noise to the system. Without the diplexor, the weaker receive signal could be drowned out by the stronger transmit signal.

The next stage of the research was to operate the system on board the aircraft as it flies above the airfield. This requires an onboard power supply supplied by an Uninterruptable Power Supply (UPS). A UPS functions by converting energy stored in batteries from DC into AC in order to provide backup power in the event of a loss of grid electrical power. For the experiment, the portable UPS will replace the electricity previously supplied from the electrical grid for the onboard equipment. In a real-world scenario, the network equipment would be connected into the aircraft electrical system to ensure the continued operation of the system, in the same manner as the avionic equipment on the aircraft. For the purposes of the experiment, to make the test implementation less complicated, the network -in-a-box and the repeater had their own power supply, independent of the aircraft's power supply.

To estimate the number of tests that should be carried out, statistical rules can be applied. This research requires an understanding of the statistics that drive sample size decisions (Smith, 2013). In order to calculate a sample size, the population size and confidence interval and standard deviation are required.

The population size is the total number of SMS messages that could be sent. In this case, it is an extremely large and unknown number. It is common for the population of SMS messages to be unknown or approximated (Smith, 2013). The confidence interval or margin of error determines how much higher or lower than the population mean the sample mean can be. The confidence level is how sure it is that the actual mean falls within the confidence interval. For this research, a figure of a 99% confidence level will be used. The standard of deviation is a measure of how much variance is to be expected in the responses.

The confidence level corresponds to a Z-score available from a table. This is a constant value needed for this equation. For a 99% confidence level, the Z-score is equal to 1.96 (SJSU, 2007). The formula for sample size for an unknown population size or a very large population size is given by:

$$\text{Sample Size} = (\text{Z-score})^2 * \text{StdDev}*(1-\text{StdDev}) / (\text{margin of error})^2 \qquad (8)$$

For a 95% confidence level, 0.5 standard deviation, and a margin of error of +/- 1%, the formula calculates as:

$$((1.96)^2 \text{ x } .5(.5)) / (.01)^2$$

$$(3.8416 \text{ x } .25) / .0001$$

$$0.9604 / .0001$$

Therefore 9,604 samples will be needed. This is the number of samples for testing in a lab environment to prove statistical significance.

CHAPTER IV

RESULTS

The Airborne Communications Network (ACN) is planned as a system that can facilitate emergency communications in the aftermath of a disaster. The ACN will have a set number of possible users within a specific coverage area, and will offer a defined set of services. These limitations are placed on the system to prevent the system becoming overloaded and to limit the scope so a functional system can be produced. The system is designed to offer communications facilities in the event of a complete failure of the ground-based cellular network in the wake of a catastrophic event.

Initial tests were performed with one test phone sending an SMS message to another test phone. The purpose of this experiment was to adjust the basic functionality of the system. By basic functionality this was did the unit power up correctly and could it perform the very basic tasks of making and receiving voice calls and SMS messages. The network parameters of a GSM system were set to the default values for the most part, with the major deviation being in the bias of the settings toward SMS message communication instead of voice communication. The intention of the indoor laboratory environment test was to prove the system worked and to gauge the system performance when it was very lightly loaded with SMS traffic. A single phone sending to another phone is the most basic test of a phone network. In these tests, the average end-to-end time for the transit of an SMS message was nine seconds when 700 test messages were sent.

A further system test took place using a trial rig of 15 cellular terminals sending messages to 15 other devices. This experiment expands on the early one terminal to one terminal test to expand it to a multiple terminal to multiple terminal test. These multiple test phone boxes were controlled using two laptop PCs running software called *SMSCaster*. This software allowed SMS messages to be created in bulk and then to be programmed and dispatched to multiple numbers. Messages created were on average 57 characters long. The SMSCaster software added an advertising suffix to the test messages, and this was on average 57 characters in length. As was discussed previously in this chapter on page 57, the average length of an SMS message is 51 characters, so 57 characters was a conservative approximation of the average length of a user's SMS (Battestini, 2010). Over 16,000 SMS messages were sent between the test terminal banks, with an average time to send being around eight seconds and an end-to-end time of around 19 seconds, as shown in Table 9. From the methodology section, 16,000 SMS messages was judged a large enough sample size to ensure a statistically significant result; having assumed a 1% margin of error and a 99% confidence level, the recommended sample size is 9,064 samples (Raosoft, 2004).

Nine SMS messages were lost in the transmission through the system. Nine losses in 16,340 total SMS messages sent is a success rate of 99.99945% or failure / blocking rate of 0.00055%. The grade of service or blocking was assumed to be 3%, so this very low level of blocking falls well within the allowed parameters. The reason there was blocking and subsequent failure to send at all is that the sending software SMSCaster has a limit to the number of retries it makes to send an SMS message. After five attempts, the software does not retry. The SMS message is left in the SMS broadcast software output queue and marked as unsent. When the sending terminal tried to send the SMS message, it could be that all the radio resources were occupied, but it is more likely that the limitation was with the SMS-C server component of the OpenBTS platform. This is because there were 52 dedicated radio resources being used by 15 transmitting and 15 receiving terminals. Thirty devices using 52 resources to send the SMS messages leaves a large capacity margin.

The OpenBTS network was configured with settings for 52 SDCCH channels and one full traffic (TCH) channel. A TCH is used to carry speech and data traffic. SDCCH channels are the channels in the GSM system that handle text messaging, whereas the TCH channel handles voice and data calls. As the system was being used to exclusively handle the SMS message, the system configuration was biased toward carrying this type of traffic. The OpenBTS software would not allow the network to be configured without at least one TCH, hence the mix of 52 SDCCH and one TCH.

This part of the experiment in the indoor setting went well and proved the test system would work. The test also proved large numbers of SMS messages could be successfully processed by the OpenBTS system with a reasonable system performance in terms of throughput and time to transmit a message. This phase of the experiment also allowed the OpenBTS network-in-a-box to be successfully configured, and the parameters changed from the default values to better suit the needs of the specific experiments.

Table 9

Result of Sending Multiple SMS messages in Lab Environment

Av. time to send	Av. time to receive	No. of SMS lost	No. of SMS sent
8.25	21.75	0	400
6.8625	21	0	400
9.642857143	20.35714286	0	140
7.960714286	17.42142857	0	1400
7.944642857	18.25714286	1	2800
8.55	17.98928571	3	2800
8.228571429	17.67857143	2	2800
9.225	17.1375	3	5600
8.333035714	18.94888393		16340

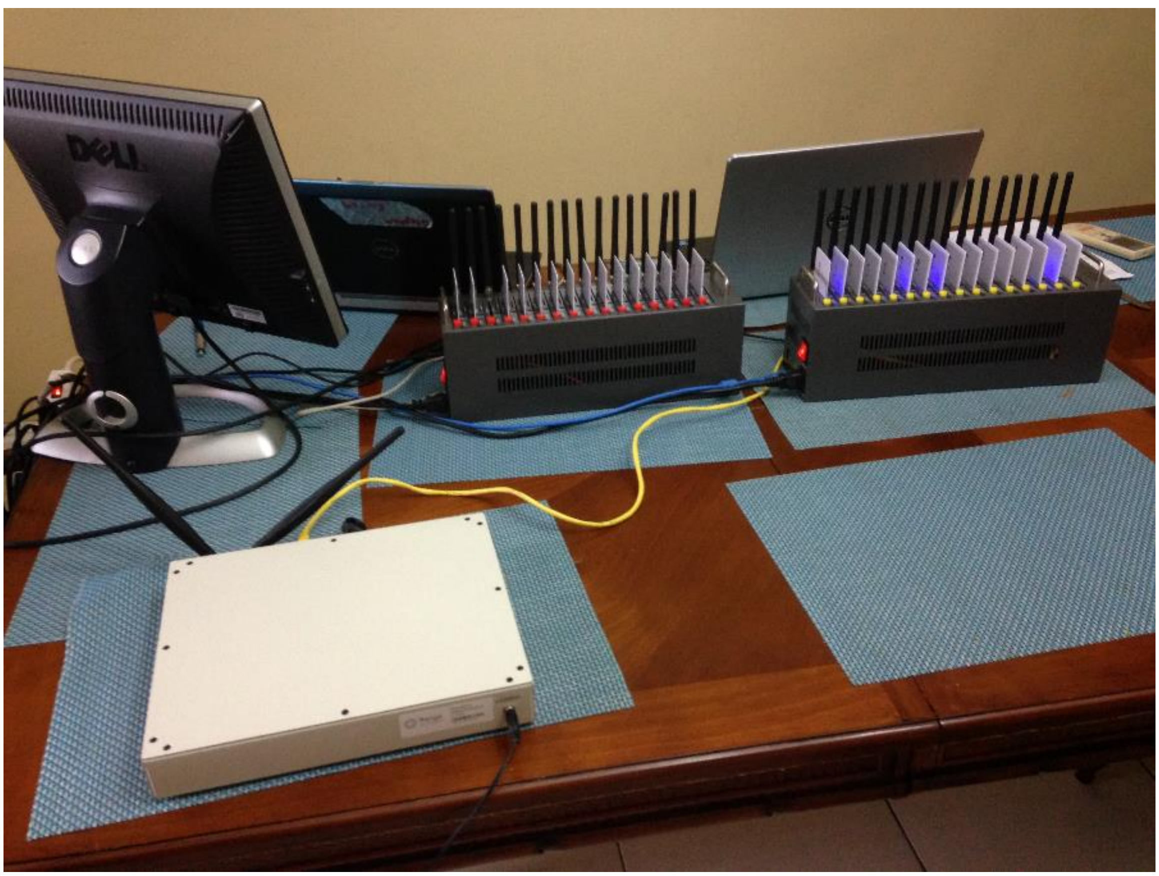

Figure 13. Test network with multiple SMS send and receive capabilities.

Operation of Network in Outdoor Environment

The testing of sending SMS messages between terminals was then tried in an outdoor test case. The OpenBTS was connected to an external antenna on a wall exterior to the house. The test phones were brought outside, and the sending of SMS messages between devices was attempted. Testing of the network-in-a-box in the outdoor environment showed a marked degradation in system performance. The maximum range achieved was 30m (100 feet) for successful communications to take place between the handset and the base station antenna. This is an extremely limited range, similar to a cordless telephone in a house. The network-in-a-box OpenBTS system for outdoor use needs a greater performance range to be of practical use in an outdoor environment. The transmit power of the test network is relatively low at 20 dBm or 0.1 Watts. The transmit power of the OpenBTS test network is low, compared to that of the GSM cell phone that has a maximum transmit power of 33 dBm or 2 Watts. The difference in power between uplink and downlink creates an imbalance, where the handset range is greater than the base station coverage. An imbalance means that the base station can pick up the phone's transmissions, but the phone cannot receive the base station's transmissions. The system will not work correctly when an imbalance of more than 5dB exists between phone and network (Sharma, 2012).

In order to rectify this imbalance, a signal amplifier was added to the transmit path. The amplifier boosts the weaker transmit power of the base station, thereby improving the system performance in the outdoor environment. Figure 14 details this network configuration with the external amplifier and diplexor detailed.

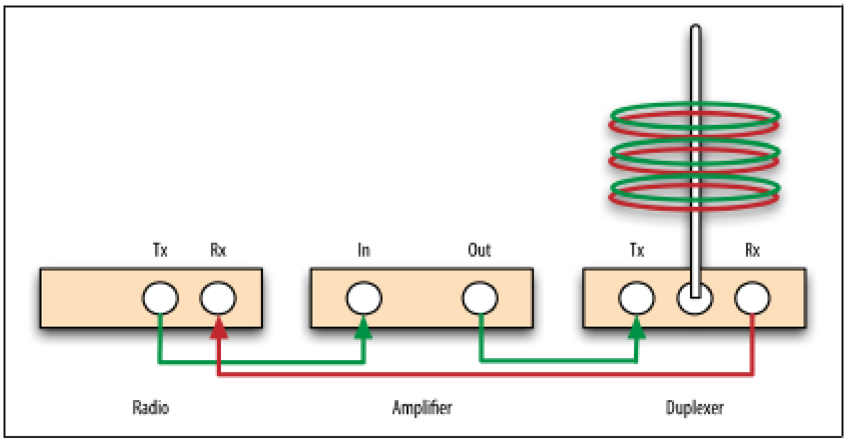

Figure 14. Configuration of test network for outdoor environment.

In order to amplify the weaker downlink signal from the network to the cell phone, an amplifier is used. A cellular repeater was sourced and configured to act as a downlink power amplifier. A *repeater* is a device that receives incoming signal and retransmits the signal, adding power (Telco Antennas, 2016). Unlike a cellular phone cell site, a repeater does not interpret the signal in any way, and hence, any incoming signal on the repeater's frequency will also be retransmitted. A cellular repeater is typically used to boost coverage in a small area such as a stretch of road with poor coverage or an office or hotel where indoor environment factors such as concrete walls attenuate the cellular signal.

The amplification provided by the repeater extended the range of the network compared to the network configuration used in previous outdoor trials. The repeater is a band-selective repeater that can be configured to boost a certain band of channels within the 900 MHz frequency band. This configuration is done so that the repeater only boosts signals assigned to one operator within their assigned frequency band. Figure 15 shows that the band between GSM900 channel 1 and 10 was enabled. The repeater was configured with a fixed gain of 90 dB in the downlink and 60 dB in the uplink, as shown in Figure 16. Figure 17 shows the uplink gain attenuated by 25 dB to give the best performance of the uplink without saturating the receiver of the base station.

Channel No.

RF Parameter Information

Parameter Grouping

Item Select	Parameter Name	Status	Setting	MinValue	MaxValue	Unit	Remark
Parameter Grouping : Edge Channel No.							
☐	Working Band High Edge Chai	10		0;975	124;1023		Uplink : 892MHz;Downlir
☐	Working Band Low Edge Char	1		0;975	124;1023		Uplink : 890.2MHz;Dowr

Figure 15. Screenshot of band of operation of GSM repeater.

Gain

RF Parameter Information

Parameter Grouping

Item Select	Parameter Name	Status	Setting	MinValue	MaxValue	Unit
Parameter Grouping : Gain						
☐	DL Gain	90	N/A			dB
☐	UL Gain	65	N/A			dB

Figure 16. Screenshot of gain settings of GSM repeater.

ATT

RF Parameter Information

Parameter Grouping

Item Select	Parameter Name	Status	Setting	MinValue	MaxValue	Unit
Parameter Grouping : ATT						
☐	DL ATT	0		0	30	dB
☐	UL ATT	25		0	30	dB

Figure 17. Screenshot of attenuation settings of GSM repeater.

A higher amplification increased the system noise and reduced the sensitivity of the receive path. When the receiver background noise is too great, the receiver struggles to pick-up and detect the weaker transmission from the cellular phone. The repeater output power and attenuation needed to be set by the repeater control software in such a way as to maximize the performance. The repeater parameters are adjusted one at a time, and the system performance tested to ensure the optimum settings were found.

There is a significant variation in system performance between a cellular system in an indoor test environment and in an outdoor environment. In an outdoor environment, the issues of external noise and the distance and environment through which the cellular transmissions have to traverse become much more significant factors. Radio signals experience multiple path fading as they travel over the air interface between the terminal and the BTS. Radio signal attenuation occurs and is due to the radio transmissions having to pass through trees, buildings, and other obstacles. Multipath fading occurs as reflected signals destructively interfere with other signals to reduce the overall signal strength and quality of the received signal. In addition, other cellular users and cell phone towers' emissions add to the general overall radio noise level in the environment, further degrading system performance.

Operation of the OpenBTS Network with Connection to an Aircraft

For the initial test with the aircraft, the equipment was placed on the ground adjacent to the aircraft. The equipment for the test consisted of the OpenBTS network-in-a-box, the diplexor, the cellular repeater, the UPS power supply, and the ancillary power and RF cables. The equipment was set up and connected to the external *Distance Measuring Equipment (DME)* antenna of a Cessna 172N light aircraft.

The DME equipment functions using the L Band at a frequency range of 978-1213 MHz (Rogers, 1998). The L band occupies the portion of the spectrum above and adjacent to the GSM900 band which occupies 890 to 960 MHz, so the DME antenna can function in the GSM900 band as well. The DME antenna, even though designed to operate in a particular frequency, can work in adjacent frequency bands with slightly reduced performance gain.

Figure 18 shows the equipment on the ground and the location of the shark fin DME antenna on the bottom of the aircraft fuselage. The repeater and the OpenBTS network in a box equipment required an 110V AC supply, so this stage of the experiment was conducted with all the equipment connected to the hanger building's electrical supply via an electrical extension lead. This part of the testing verified the performance of the system in an outdoor environment with all the components of the system, the network-in-a-box, the diplexor, and the repeater in place. Multiple test SMS messages were sent and received while the aircraft was on the ground at a distance of up to 300 meters from the aircraft. This ground test served as a dry run for the later test where the equipment would be taken into the air. This experiment proved that the network would operate successfully using the onboard DME antenna. It also allowed for the location and connection of the equipment once on board the aircraft to be planned.

Figure 18. Initial configuration of test network for outdoor environment. The DME antenna is the inverted shark fin on the bottom of the aircraft fuselage in the top right of the photograph.

Full Network Operation Test

The ground test rig of the two banks of test phones was set up on a table in an area outside a hanger with good visibility of the sky as shown in Figure 19. Fourteen test phones from one bank were configured to send messages to sixteen other test phones on a separate band of terminals. The equipment was installed on the aircraft, configured and tested again while the aircraft was on the ground. As before, test SMS were sent and received by the system.

Figure 19. Configuration of test network for outdoor testing prior to installation on aircraft. Shown are the Range Networks network-in-a-box and the two banks of test phones.

Tinson Pen in Kingston is an uncontrolled aerodrome with a 4,300-foot asphalt runway (AAJ, 2007). The DME equipment on board the aircraft carrying the network-in-a-box could not be used, as the DME antenna had been re-tasked to operate as the antenna for the ACP. As the aircraft was flying under visual flight rules and within the aerodrome traffic pattern, the DME was not required for the safe operation of the aircraft.

The weight and balance of the equipment on the aircraft were checked to ensure there were no center of gravity problems when the equipment was loaded on the back seat of the Cessna 172 aircraft. The network-in-a-box and the ancillary equipment were loaded onto the aircraft. Electrical power for the equipment was provided using a UPS that was located in the baggage compartment of the aircraft. A further ground test was performed, and the test network was verified as functioning correctly. During the ground test, the system successfully sent 1,038 SMS, as shown in the results Table 10 The two banks of test phones were located approximately 10m from the test aircraft.

Table 10

Result of Sending Multiple SMS messages in Outdoor Environment Onboard Aircraft

Av. time to send	Av. time to receive	No. of SMS lost	No. of SMS sent
6.26	19.58	1	1038
9.25	28.67	32	56

The equipment was loaded onto the aircraft as shown in Figure 20. Following a further successful retest of the equipment on the ground, the aircraft taxied from the ramp area with a test pilot and system operator on board. The aircraft pilot performed the standard run up checks to ensure the safe operation of the aircraft, and a further system check of the communications system was performed as the aircraft was on the runway waiting to take off. The system performance was verified by the sending and reception of a test SMS message between a ground user and the aircraft when the aircraft was at the holding position on the runway.

Figure 20. External view of installation of network equipment on the aircraft.

The aircraft took off from the aerodrome and flew in the pattern for a period of 30 minutes, at an average altitude of 500 feet. The bank of test phones configured to send SMS messages continuously tried to send text messages, and once the aircraft came into range, the SMS messages were transmitted by the test phones and travelled over the air to the ACP. The onboard network-in-a-box processed these text messages and transmitted the SMS messages to the second bank of test phones on the ground. Successful two-way communications between the ground and aircraft were established once the aircraft came within approximately 1,000 feet of the ground equipment. The time window when the batch of SMS messages could be successfully transmitted and received when the aircraft was travelling overhead was short, in the region of less than one minute.

During the brief period the ACP was in range, the two banks of test phones had to acquire the ACP GSM beacon signal, connect to the network, and then begin to send the SMS messages as ordered by the SMSCaster software. Reception of the text message by the second bank of phones followed the same process. The process to register on the network took between 10 to 20 seconds during the experiment. This network registration and authentication needs to take place before the phones can send or receive SMS messages.

The uninterruptable power supply was able to provide power to the network equipment for a period of 25 minutes. The short time the aircraft was in range of the ground-based terminals limited the number of SMS that were sent and successfully received. The Airborne Communications Network successfully transmitted and received 24 SMS messages during the course of the airborne portion of the experiment. While a larger number of successful text message transmission would have been desirous, even the transmission and subsequent reception of a single SMS message from an aircraft overhead proves that the system works in a real-time test. Background radio interference from the terrestrial cellular network on the ground imposed limits on the ACN performance. In a large city like Kingston, Jamaica, there are a large number of cell sites transmitting and an even larger number of cell phones transmitting. Even though the ACN was configured to use a GSM frequency not used by the licensed cellular operators, there was still a large amount of background signals in the air that are viewed by the network-in-a-box BTS as external noise. If the ACP were to be deployed in the aftermath of a disaster as envisaged by this research, the terrestrial cellular network would be off-air and non-functional, eliminating this interference issue.

CHAPTER V

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of the research was to model and demonstrate how an airborne communications system could be used to facilitate communications in a scenario such as the aftermath of a natural disaster. This section includes a discussion of the results for the analyses conducted followed by the conclusions and recommendations for future research and practices.

In the research, the theoretical aspects of such a system were discussed in terms of the likely function, performance, capabilities, and operation. The system inputs were defined using a small Caribbean island as a test case. This particular test case was examined in order to ensure the scope for the project was specific, measurable, achievable, and realistic. The modeling of the system performance was completed for a specific set of parameters. The theoretical network performance was calculated.

The real-world test system was then assembled from individual components in a step by step manner, with new pieces of equipment being added to the overall system in a piecewise and methodic manner. By the use of off-the-shelf components, a test system was assembled that constituted a realistic representation of a full-scale communications system. As GSM is a mature technology, the equipment used was relatively inexpensive and reasonably easy to source.

Discussion

Research question. The original research question asked: How can an airborne, emergency wireless communications system be modeled to provide design guidance on cellular communications service for use in disaster-aftermath related scenarios?

The literature review provided the background research, showing the work to date in related areas, but revealed a gap in the research in terms of the actual testing of an airborne system in a real-world environment. The research examined an airborne system that would allow point-to-point SMS messages to be sent with the ACP as the central hub facilitating the exchange of the messages. The SMS-based solution was selected as the best system, as it provided the most connectivity and best usage of the scarce network resources in the wake of a disaster.

Rogers (2012), in his research on using a man portable UAS for hosting GSM, could not mount the telecommunications equipment on a UAV due to time and regulatory issues. This research did manage to mount the equipment and show by experiment an airborne platform could relay GSM communications successfully.

Frazil et al. (2008) proposed an emergency communications system using a compact, ruggedized satellite terminal that could be used for communications in an emergency. This solution used backhaul over satellite to transport the GSM cell site traffic to the core GSM network infrastructure located away from the disaster area. The proposed system would be functional but would not be a standalone system, and the limited coverage of the system would restrict the system usefulness. The airborne, self-contained communications system, as researched in this dissertation, could work in a standalone fashion and could move within a disaster area to improve the system reach.

Wypych et al. (2012) described a system for GSM communications using an off-the-shelf GSM mini base station mounted on a small UAV. The UAV hosted a small BTS and then used a Wi-Fi radio link to connect to the core network on the ground. This research continued from this concept and removed the need for a Wi-Fi link by using a miniaturized core network, making the emergency communications system autonomous. By making the UAS autonomous, the system can work independently of communications infrastructure on the ground, making the solution more transportable. The self-contained nature of the UAS allows the system to operate more independently than a system with both airborne and ground components.

Tuna et al. (2014), in their research on an UAV-aided communications system for disaster recovery, stated that an area where there was a knowledge gap was in the lack of field tests or experimental validation of using UAVs for communications. This research has begun to bridge this gap by demonstrating how an airborne communications system can be brought from a conceptual level through to a real-world field trial.

The SMS-based system was modeled mathematically, and the calculations to show the likely system performance were made. The theoretical calculations led to the conclusion that such an ACP system was feasible and that the research should continue to the trial stage. The equipment necessary for a real-world trial was sourced, and the experimentation continued in the indoor test environment. As the testing and experimentation continued, changes and adjustments to the system configuration were made to improve the system performance. This iterative process improved the operation of the communication system.

Following the completion of the testing of the system in an indoor lab type environment, the next phase of testing took place with the test terminals in an outdoor real-world setting. This testing brought new challenges in terms of dealing with external factors, such as now having to deal with radio interference and having to change the antenna configuration to allow for the transmission and reception of radio signals on the same antenna.

The final stage of the research was to evaluate the system performance through an actual demonstration of the test system in a real-world setting in order to ensure the original system requirements were satisfied. The test network was configured aboard a light aircraft. SMS were successfully sent and received from an airborne aircraft between test phone terminals positioned on the ground.

Conclusions

This research proved it was possible to model an Aerial Communications Platform (ACP) once the specifics and performance of the platform were clearly defined. The communications network tested supported the telecommunications services envisaged at the start of the research. By facilitating the transmission of SMS, the ACP allowed the exchange of information, and this ability to communicate is better than having a complete communications blackout, as is frequently the case in the wake of a natural disaster.

The ACP is limited by the fact the system only allows the transmission and reception of point-to-point text messages. This factor limits the reach of the network to only users within the disaster area and only allows messages to be sent among these users. Third party connections to networks or users outside the coverage provided by the ACP cannot be reached.

Theoretical calculations for the system performance predict a better system performance than revealed by the experimental results. It was calculated that it takes 1.92 seconds to send an SMS, whereas the actual value from the experimental results was 8.33 seconds. One of the reasons for this difference in performance can be attributed to environmental factors such as external radio frequency interference. The theoretical performance of the OpenBTS network-in-a-box hardware, particularly the speed at which SMS were processed by the SMS-C component, demonstrated a notable difference between the calculated and experimental values. This difference in values is also due to the fact that in a large network, an SMS-C is a standalone component, usually a dedicated server. In the OpenBTS implementation of a network-in-a-box, the SMS-C software is just one of the components of the network that use the shared common hardware of the system. The SMS-C in the OpenBTS system is a software block in the same way the MSC, BSC, and BTS are software components of the overall system running on a shared LINUX hardware platform. OpenBTS software based GSM network does not enjoy the same performance as a larger commercial grade network, but it costs a fraction of what a full GSM network deployment would cost. Open source technology has enabled small GSM networks to be built using open source hardware and software for a fraction of the cost of a full cellular network (Back, 2012). Software defined networks and open source software code allowed once complex and physically, relatively large network elements to be implemented at a much-reduced cost and within a shorter timescale without having the requirement to have access to a team of specialist network engineers and system integrators. For the purposes of this research, the cost factor involved in building a full-scale network would be prohibitive.

As demonstrated, the ACP system, using the OpenBTS network-in-a-box, is practical in the current time; whereas, even five years ago, a standalone GSM would be far too expensive and complicated to implement in terms of the amount of dedicated hardware required. Each individual component of the GSM system traditionally has dedicated hardware and software components. These network elements have been traditionally developed by the large telecom equipment vendors such as Ericsson, Lucent, or Huawei. These vendors made proprietary equipment that could not be miniaturized in such a way as to allow them to be easily carried aloft a small airborne vehicle.

A test network from OpenBTS could be enhanced by selecting a larger, costlier model from the supplier. The core network components would be similar in functionality, but by adding extra transceivers (TRX) and larger power amplifiers, the radio network performance would be enhanced. This solution would be more like an integrated flying cell site as opposed to a test lab network enhanced for outdoor operation by the addition of third party components. A commercial ACP would require a more powerful BTS with greater functionality and capacity to enhance the overall system performance.

In the field test performed, the network-in-a-box aboard the Cessna was overhead, restricting the period that the ACP was in range of the ground terminals. However, SMS were successfully sent and received in the testing, and with a more powerful amplifier, the system range would increase. In addition, the problem of external system radio noise limiting the radio network performance would be negated, as in the wake of disaster; the ground network would be damaged and therefore, be off air. Radio noise is a disturbance generated by an external source that affects a radio system. Without the ground transmissions to interfere with the radio performance, the background radio noise would be much reduced. Background noise in a radio network typically drops by 10 dB between the highest traffic hour of the day and the lowest traffic hour of the day. The background noise would therefore by at least ten times lower in the event the ground network was inactive.

In order to power the experimental equipment on board the aircraft, a UPS was used. This battery powered device had the ability to provide 25 minutes of power to the equipment. In a more permanent non-experimental solution, an alternative to the UPS would be used to provide power. The communications equipment would be powered by the aircraft's electrical system, not independent of the electrical system aircraft as was the case in the experiment.

For a manned aircraft, the endurance of the system is limited by the physical endurance of the pilot(s) and the ability to refuel the aircraft in flight. By using a UAV, the endurance of the pilot does not arise as a limiting system performance factor. A UAV can be configured to fly a repetitive track around the required coverage area. Fuel availability and the consumption of the UAV would now be the limiting factor in the system endurance.

Using a tethered balloon or aerostat would improve the system endurance and performance in terms of providing consistent coverage to an area, weather permitting. The coverage area would be fixed, but the system endurance would not be reliant on the availability of fuel for the aircraft engines. In this case, power could be provided via a tether to the ground or by using a combination of solar panels and batteries. Solar powered UAVs are being trialed, with one example being the Facebook Aquila flying drone using solar panels to charge onboard batteries (Metz, 2016). These batteries, in turn, power the electric motors and onboard electronics and radios. The radios are used to provide communications to users on the ground. This aircraft is still experimental, but it shows there is continual current research in the area of uses of UAVs for communication purposes.

This research has shown that an airborne communications system can be modeled and can also be implemented and successfully tested in a realistic series of field trials. The research has shown the investigations to date in the field and how the combination of technology, especially the recent miniaturizations and move to open source software for cellular network components can allow sophisticated cellular networks to be implemented. The ACN system proposed, if developed further into a commercial product, could enable connectivity and reduce the communications problems that were experienced following Hurricane Sandy and Katrina. If telecommunications can be rapidly restored in the wake of a disaster, lives can potentially be saved, and the recovery process can begin sooner and be more effective.

Recommendations

This research showed it is possible to design and fly a communications system as envisaged in the research question. Real-world testing proved the experimental system was functional, and the proof of concept leads to possible future expansion of features and functionality of an emergency communications system. An Airborne Communications Network would allow for rapid and accurate information exchange that is essential for the disaster response period. Experience with both natural and man-made disasters highlights the fact that communications are useful only to the extent that they are accessible and useable by the population.

The study successfully researched and proposed one method to provide emergency communications services. Extensions or a continuation of the present study may also focus on more areas of providing communications, such as the provision of voice or data services. Verifying the causes of some of the system performance issues presented here was tenuous in some cases because, for example, it is not practical to turn off a live cellular phone network to allow testing of a system in a noise free environment, such as one that would exist if the ground terrestrial networks were off air.

Using a Cessna 172 aircraft, a real-world trial in a built-up area showed an aircraft in flight could be used as a relay for air to ground communications. The experimental system of the light aircraft as a host for the network-in-a-box was used as it was an expedient method to get the test platform in the air and functional. In a disaster situation, a similar ad hoc approach could be adopted, but it would be better to have the aircraft, be it manned or unmanned, set-up and configured in advance of the disaster. Certain disasters such as hurricanes in the Caribbean have a defined season. By having the system configured and in place to be made operational shortly after the disaster, the time to launch the ACN would be reduced. For the Caribbean, the ACN could be located in Trinidad, which is outside the hurricane belt, and then moved to the affected island in the period immediately following the passage of the hurricane.

A carrier grade network used in commercial service by operators such as Vodafone or T-Mobile would cost millions of dollars to implement and could not be carried onboard a light aircraft. The network-in-a-box from Range Networks was a perfect solution to successfully prove that an SMS could be sent between terminals on the ground via an ACN. The research and field experiments provided a basis upon which future work can be built.

Recommendations for Future Research

This research has focused on modeling and implementing an Airborne Communications Platform to supply a carefully defined set of services. The ACP could be expanded to offer additional services such as point to point voice communications and data connectivity. This would require a more complex network-in-a-box with greater capacity, but this is possible.

The ACP's functionality would be greatly enhanced if it could be connected to an external network. In the aftermath of a disaster, it is often difficult or impractical to set up a ground station in the area of the disaster; however, if the ACP had a connection to a satellite with coverage in the area, the ACP could then communicate with the outside world. Data communication with aircraft presents unique technical challenges, and these challenges are more pronounced when the aircraft are travelling over oceanic or other remote areas (Curran, 2014). With a suitable ground station in place with a high-speed data connection, airborne systems are available that can support high speed data services, up to one Gigabit per second (Gbps). Multimedia activities, such as video streaming, are very bandwidth intensive, and the provision of these services presents a serious technical challenge. On the ground, fiber-optic cables are the method of choice for the provision of high speed data service, and in contrast, an airborne high-speed data communications solution has to be provided wirelessly.

With a suitable connection to the external communications networks 911/999/112 emergency calls could be facilitated by the ACP. The setup of the ground station with the appropriate routing is an area of future research. In addition to this, location services could be built into the ACP system, whereby the ACP could use trigonometry and distance measurement to estimate the location of the mobile user to help with location in a post-disaster environment.

Current satellite communications systems to serve domestic fixed customers have data rates in the range of up to 15 Mbps (Brodkin, 2013). There is a broadband low earth orbit satellite system in operation called O3B, and this system has the potential to provide up to 1.2 Gbps of bandwidth (O3B Networks, 2013). Unfortunately, the system requires at least two large steerable dishes that cannot be easily mounted on an aircraft, rendering impractical the satellite broadcast communications option currently available.

The next generation of satellite communications systems, referred to as high-throughput satellites (HTS) will prove more suitable for the connection of an ACP to other networks. A HTS uses spot beam technology to increase the capacity by reusing frequencies in the same manner as a terrestrial cellular network (Gilat, 2012). Using a Honeywell Jetwave on-board terminal and the Inmarsat Global X press satellite, a speed of 50 Mbps has been achieved in airborne trials (Bellamy, 2016). Fifty Mbps of backhaul to the internet would allow excellent voice services and generally good data services to be provided by the ACP. Future research could further investigate the use of satellite backhaul to expand the services an emergency ACP could offer.

The network-in-a-box ACN could be upgraded with more capacity, in terms of more TRX with higher transmit power and an enhanced computer hardware platform with better computational power and subsequently better performance. A practical emergency communications system would have to be ruggedized and married to a full time airborne host platform such as a dedicated UAV or light aircraft with the specific hardware to allow the communications equipment to be quickly and easily accommodated on board.

In terms of a suitable host platform, research into the suitability of aerostats and powered drones as a host for the network equipment is another avenue that could be perused. Googles Project Loon and Facebook Aquila are two important projects with the purpose of using airborne platforms to provide communications. For the Facebook drone, the areas of research still being pursued concern the management of electrical power onboard the craft, improving the size and speed performance of the aircraft and the cost to deploy the technology on a widespread basis (Gomez, 2016). These are common problems for the future host of the communications platform.

Future research could further look into the energy-efficiency of the UAV. The UAV need to use the minimum amount of energy for the mobility of the platform in terms of maximizing the time the UAV can remain airborne (Zeng, 2016). The second aspect of energy-efficiency aims to satisfy the telecommunications requirement with the minimum energy usage on communication-related functions, such as communications electronics and signal transmission.

There is a definite need for communications in the aftermath of a disaster. The terrestrial networks cannot always be relied on to provide this essential component of disaster relief. This research shows that a SMS-based communications system is feasible, and there are possible areas that future research can explore by expanding the range of services that an emergency communications system could offer.

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