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QoS Based Airborne Internet Access Through Submarine Optical Fiber Cables

by

Najmul Hassan

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Dedicated to my father Muhammad Sadiq and

my Late Daughter Maryam Najam

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This is to certify that the research work presented in the dissertation, entitled "**QoS Based Airborne Internet Access Through Submarine Optical Fiber Cables**" was conducted under the supervision of **Dr. Noor Muhammad Khan**. No part of this dissertation has been submitted anywhere else for any other degree. This dissertation is submitted to the **Department of Computer Science, Capital University of Science and Technology** in partial fulfillment of the requirements for the degree of Doctor in Philosophy in the field of **Computer Science.** The open defence of the dissertation was conducted on **January 05, 2024**.

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List of Publications

It is certified that following publication(s) have been made out of the research work that has been carried out for this dissertation:-

1. **Najmul Hassan**, Noor. M. Khan, "Cost-Effective Reliable Transmission Service for Internet of Flying Things." *International Journal of Distributed Sensor Networks.*, vol. 17, no. 6, pp. 1-13, June 2021.
2. Syed. J. Nawaz, Noor. M. Khan, Muhammad. I. Tiwana, **Najmul Hassan**, Syed. I. Shah, "Airborne Internet Access Through Submarine Optical Fiber Cables", *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 1, pp. 167–177, January 2015.
3. **Najmul Hassan**, Noor. M. Khan, Ghufran Ahmed, Rodica Ramer, "Real-time Gradient Cost Establishment (RT-GRACE) for an Energy-Aware Routing in Wireless Sensor Networks", *IEEE eighth international conference on intelligent sensors, sensor networks and information processing.*, pp. 54–59, June 2013, Melbourne, VIC, Australia.

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(Najmul Hassan)

Abstract

Internet access for passengers on airplanes is considered one of the biggest unresolved challenges to widespread Internet deployment. Vast, remote ocean regions along the world's busy air routes require low-cost, reliable, high-speed Internet for aircraft. Satellite links can provide Internet coverage in such remote areas; however, their services are still costly with low bandwidth and longer delays. Fortunately, submarine optical cables laid across the oceans run along the same busy air routes. These cables can be used as a high-speed Internet backbone for wireless Internet access on aircraft. Dedicated ships stationed along these submarine optical fiber cables can be exploited to provide Internet, security, and navigation services to aircraft and ships. This dissertation proposes a novel architecture for ground/sea-to-air access network that incorporates the already-deployed submarine optical fiber cables to provide high-speed Internet access to aircraft flying over the oceans via dedicated stationed ships. The research work in the dissertation comprises two parts. In the first part, the complete design of the proposed solution is discussed in detail. Unlike the conventional land-based mobile radio cellular systems, the high speed of aircraft results in reduced available handover time. To address the challenges associated with high-speed aircraft mobility, an analysis for the impact of various parameters on handover performance is presented. Using the proposed analytical model, a mathematical relationship for the handover period with aircraft speed, aircraft direction of motion, and propagation environment is derived based on the path loss propagation model. In the second part, the Quality of Service (QoS) parameters of the proposed work are analysed. In order to acheive scalability and reliability a novel routing algorithm named as Airborne Ad-hoc Routing Algorithm (AARA) is also proposed that extends the usability of the proposed airborne Internet access scheme over the ocean in off-ship regions. A comprehensive simulation is performed to prove the effectiveness of the proposed solution. The QoS parameters of the proposed work are compared with those of well-known existing solutions. The end-to-end delay and packet delivery ratio are the two parameters used for this comparison. In order to make the comparison more comprehensive and realistic, two different scenarios are considered: one with the aircraft flying on a predetermined path and the second where the aircraft fly on random flight paths. The simulation results show that the proposed AARA outperforms the other existing systems for airborne Internet service delivery under high mobility and dynamic topology changes. In both scenarios, the proposed AARA performs much better than the existing solutions. The dissertation also discusses some possible extensions of the proposed research, where the results can be extended in various ways. For example, further studies can be conducted on the application of the proposed work in the areas of UAV, edge/fog computing, live black box, and surveillance.

Contents

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Abbreviations

2G	Second Generation Cellular Networks
3G	Third Generation Cellular Networks
4G	Fourth Generation Cellular Networks
5G	Fifth Generation Cellular Networks
A2G	Air-to-ground
AARA	Airborne Ad-hoc Routing Algorithm
A-LSR	Cross Layered Routing Approach for Civil AANET
AIC	Airborne Internet Consortium
A2A	Air-to-Air
AS	Air Station
AoA	angle-of-arrival
BP	Best Path
BS	Base station
BTS	Base transceiver station
CDMA	Code-division multiple access
DWDM	Dense Wavelength Division Multiplexing
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
EEG	Electroencephalogram
ETO	Electrical To Optical
EDGE	Enhanced Data Rates for GSM Evolution
FA	Foreign Agent
G2A	Ground-to-Air
GS	Ground Station
GRAA	Geographic Routing for AANET

GPS	Global Positioning System
GoS	Grade of Service
GLSR	Geographic Load Share Routing
GEO	Geosynchronous Equatorial Orbit
GSM	Global System for Mobile communication
GPRS	General Packet Radio Service
HA	Home agent
HLR	Home location register
HA	Home Agent
HAPs	High-Altitude Platforms
IoT	Internet of Things
ISP	Internet service provider
IoM	Internet of Me
IME	In-flight Medical Emergency
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
LTE	Long-term evolution
LoS	Line of Sight
LEO	Low-Earth-Orbit
MANET	Mobile ad-hoc Network
MMOGs	Massively multiplayer online games
MEO	Medium Earth Orbit
MIMO	Multiple-Input Multiple-Output
MSC	Mobile Switching Centre
NAC	North Atlantic Corridor
NTN	Non-terrestrial Network
OS	Oceanic station
OTE	Optical To Electrical
OFMDA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiple access
PSTN	Public switched telephone network
PDR	Packet Delivery Ratio
P2P	Point-to-point

QoS	Quality of Service
RAT	Radio Access Technology
RT-GRACE	Real-Time Gradient Cost Establishment
SATS	Small Aircraft Transportation System
SBP	Second Best Path
SDH	Synchronous Digital Hierarchy
SatComs	Satellite communications
TBP	Third Best Path
USRP	Universal Software Radio Peripheral
UAVs	Unmanned aerial vehicles
UMTS	Universal Mobile Telecommunications Service
UOFC	Underwater optical fiber cables
V-EEG	video electroencephalography
VLEOs	Very Low Earth Orbits
VLR	Visitor location register
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

Chapter 1

Introduction

This chapter presents an introduction related the work done in the thesis. In Section 1.1, an overview of the topic is given whereas Section 1.2 introduces the topic of airborne access. Section 1.3 describes landline optical fiber cables whereas, Section 1.4 explains underwater optical fiber cables. Landline cellular mobile networks are explained in Section 1.5. Section 1.6 and Section 1.7 discuss wireless local area network standards and satellite networks respectively. Routing Airborne Communication is introduced in Section 1.8. Research objectives are presented in Section 1.9 whereas Thesis contribution is presented in Section 1.10. Applications of the proposed research are highlighted in Section 1.11. List of publications and thesis organization are presented in Section 1.12 and 1.13 respectively.

1.1 Overview

In today's world, the Internet has evolved into an integral component of the communication environment. Beyond transforming conventional mail, banking, commerce, and entertainment systems, the Internet has spawned novel methods of information sharing, social interaction, and connecting with others. The prevalence of modern mobile communication systems has also led to a growing number of land mobile passengers gaining access to the Internet [1]. In addition, passengers traveling globally by aircraft also demand Internet access during their journeys. Utilizing travel time for Internet use while in transit is an effective means of optimizing their valuable time. Onboard, passengers can engage in various social activities, such as chatting, attending meetings through video and audio conferencing, accessing email services, and browsing the Internet [2]. The development of the information society has undeniably propelled the growth of mobile communications and Internet accessibility, both of which are increasingly crucial in the evolving information society. The Internet has not only transformed traditional banking, mail, entertainment, and business systems but has also established new avenues for information sharing and social networking.

The advent of modern mobile communication systems has expanded Internet access for mobile users. Data transfer speed plays a pivotal role in maintaining connectivity, particularly for transferring substantial amounts of data such as high-definition video, audio, images, and large text files [3]. With the prevalence of landline broadband and wireless networks, high-speed Internet is now ubiquitous in many households and businesses globally. Nevertheless, maintaining connectivity on the move remains challenging. Vehicles like cars, buses, trains, and even commercial airplanes without network access pose obstacles to Internet and communication [4]. Due to affordability and technological advancements in the aviation industry, air travel is becoming an increasingly popular mode of transportation [5]. The global average number of daily commercial flights approaches 200,000. According to the Swedish global flight tracking service FlightRadar24, a record-breaking 202,157 flights were recorded on June 29, 2018 [6]. This number is expected to rise shortly. It is noteworthy that water covers a sizable portion of the Earth's surface, forcing most flights to fly over oceans. For instance, the North Atlantic Corridor (NAC) stands as one of the busiest long-haul aviation routes globally, witnessing approximately 1,300 planes passing through it each day [7].

1.2 Airborne Internet Access

Annually, approximately 4 billion individuals partake in commercial flights worldwide, the majority of whom carry Internet-connected devices [8]. With an average of 100 passengers per plane, each passenger brings 2 to 3 Internet-connected devices, including smartphones, laptops/tablets, and various medical devices [9] [10]. These devices necessitate not only fast and reliable Internet access for staying connected globally but also seamless connectivity for diverse purposes, such as personal eHealth monitoring via smart wearables. Consequently, fast and reliable in-flight Internet access, often referred to as Airborne Internet, is imperative. In recent years, increased attention has been directed towards providing Internet access in the passenger cabin of commercial airlines [11]. Service providers in this domain include Connexion by Boeing (now defunct), AeroMobile, Panasonic Avionics, and OnAir. Given the substantial distances covered during transcontinental flights, satellite communication emerges as the most effective and convenient means to maintain a connection between the aircraft and the ground throughout the journey. This is particularly crucial for long-haul flights, often traversing oceans and remote areas such as large bodies of water, deserts, and polar regions where ground-based communication equipment is inaccessible. While direct ground-to-air cellular networks, exemplified by AirCell in the United States, are under development to offer faster and more affordable communication for continental flights, satellite communication remains the primary means of connection for transcontinental flights. Direct ground-to-air (G2A) cellular networks extend to air-to-air mesh networks, presenting a new paradigm for in-flight connectivity over oceans and remote areas. Self-organizing wireless networks generated by aircraft through direct air-to-air (A2A) radio links are termed Airborne Mesh Networks.

Originally conceived in the context of military aviation, the concept of Airborne Internet was introduced in 1999 as part of the Small Aircraft Transportation System (SATS) at the NASA Langley Research Centre Planning Conference [12]. The notion of a peer-to-peer communication network between aircraft was discussed during a conference session, leading to the formation of the Airborne Internet Consortium (AIC). The AIC was established to advocate for and support the development of such a system, with consortium members including Aerosat, United Airlines, and C3D Aero.

1.3 Landline Optical Fibre Cables

In daily life, various methods of information transmission are encountered. The awareness that speaking into a landline telephone involves the transmission of our voice sounds through a telephone wire into a wall socket, and subsequently, these sounds are carried to the local telephone exchange by a second telephone wire, is commonplace. The operation of a cell phone differs from a landline phone as it involves the sending and receiving of information through invisible radio waves.

There is a distinct operational method in optical fiber technology compared to other methods. Information is transmitted through a tube made of glass or plastic using a beam of light to encode the information. Engineers modified the same technology in the 1960s for high-speed telephone calls after developing it in the 1950s for endoscopes, which allowed doctors to see inside the body without invasive procedures.

This adaptation enabled the transmission of telephone calls at the speed of light, albeit slowed by about two-thirds in an optical fiber cable, compared to its speed in a vacuum (normally, 186,000 miles, or 300,000 kilometers per second).

As suggested by the name, fiber optic cables are composed of optical fibers—thin strands of glass or plastic. A cable may contain as few as two strands or as many as several hundred strands. Notably, each fiber optic strand measures approximately one-tenth as thick as a human hair and can handle 25,000 phone calls simultaneously, allowing a fiber optic cable to accommodate several million calls. Currently, the record for 'single-mode' fiber stands at 178 TB/sec (trillions of bits per second), potentially supporting one billion zoom sessions [13, 14].

Fiber optic links, as implied by the name, are frequently employed for transmitting data between two different locations at a distance of several kilometers using all-optic (light-based) technology. Suppose the aim is to use fiber optics to send data from a computer to a friend's house around the corner; fiber optics will be the chosen medium. Connecting a laser to your computer facilitates the conversion of the electrical data stored on your computer into a series of light pulses. This conversion is executed using the electrical data stored on your computer. The fiber optic line will then have a laser beam fired along it, subsequently detected by a detector. Upon passing through the cable, light beams will emerge from the other end. To interpret the light pulses into electrical data, necessitating a receiver's computer, our acquaintance would require a photoelectric cell, a light-detecting component.

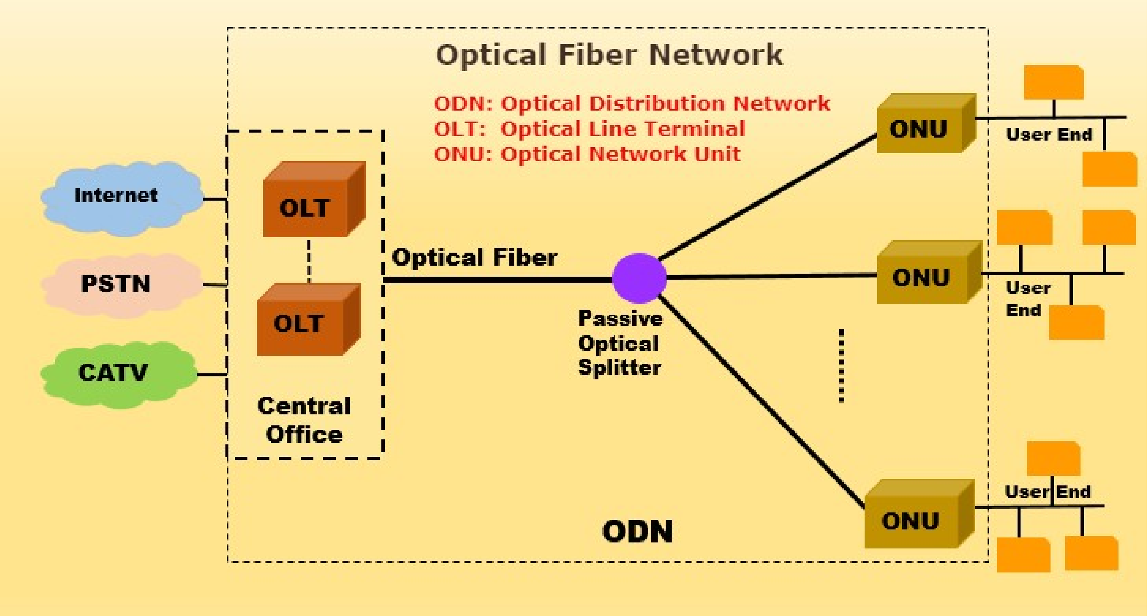


FIGURE 1.1: Landline Optical Fiber Cable Archicture [15].

Despite being a significant advancement in the telecommunications industry, landline optical fiber cables continue to experience rapid growth due to their capacity to transmit large volumes of data, aligning with the requirements of almost all modern applications. However, connecting different continents using landline optical fiber cables is unfeasible because the majority of the Earth consists of water. Consequently, underwater optical fiber cables have been developed. Figure 1.1 provides an overview of the functions of optical fiber cables.

1.4 Underwater Optical Fiber Cables

After the invention of fiber optics, this technology soon spread all over the world.

Optical fiber cables are typically deployed to connect cities on land. However, when it comes to establishing communication across oceans, where vast bodies of water separate continents, it is not feasible to achieve this using traditional fixed optical fiber cables. Therefore, alternative solutions for oceanic communication need exploration. One viable approach for such communication is through the use of satellite technology.

One solution for such communication is satellite. But satellite communication is not ideal due to huge delays and costs. The satellite is positioned in an orbit at a distance of nearly 36,000 kilometers from the Earth's surface. So to ensure successful data transmission, the data would have to travel a total distance of 72000 kilometers. Such a long distance causes a significant delay in receiving the signal. More precisely, it causes a huge latency that is unacceptable for most Internet applications. The other solution for such communication is complicated networks of specially designed optical fiber cables connecting the data center and the end devices across oceans, called undersea fiber optic cables or simply underwater optical fiber cables (UOFC) cables. These cables connect different continents that are separated by large expanses of water. Installing UOFCs requires a special cable and a ship for the pulling process. The cable being laid in the ocean needs specific engineering. Usually, after a few miles in the ocean, repeaters are used to amplify the light (almost every 50 miles) so that the signal reaches the other side of the ocean [16]. Also, the cables that are laid in shallow water near the shore or commercial fishing areas require more protection.

The exponential growth of the Underwater Optical Fiber Cable (UOFC) network, both in terms of number of connections and total capacity, has been driven by the growth of global Internet traffic. To meet the insatiable demand for digital communications, the 750,000-mile cable connects virtually every part of the globe and is critical to closing connectivity gaps [17, 18]. UOFC, also called submarine data cables, are the critical infrastructure of the digital age. The data for financial transactions, email messages, phone calls and hotel reservations etc. are transmitted over these cables, which account for up to 99 percent of all intercontinental digital communications. Despite the development and deployment of wireless and satellite technologies, submarine cables will continue to be the fastest, most efficient, and least expensive way to transmit digital information around the world in the near future. With the increasing use of the Internet, the importance of cloud computing, and the potential services of 5G networks, artificial intelligence, and the Internet of Things (IoT), the world's reliance on submarine cables will increase significantly. The basic architecture of the underwater optical fiber cable is shown in Figure. 1.2. While communication has been revolutionized by optical fiber cables, their inherent physical limitations prevent direct connections to all devices. This limitation is particularly apparent in mobile devices, such as smartphones, tablets, and laptops, designed for portability and requiring wireless connectivity. To address this need, cellular mobile

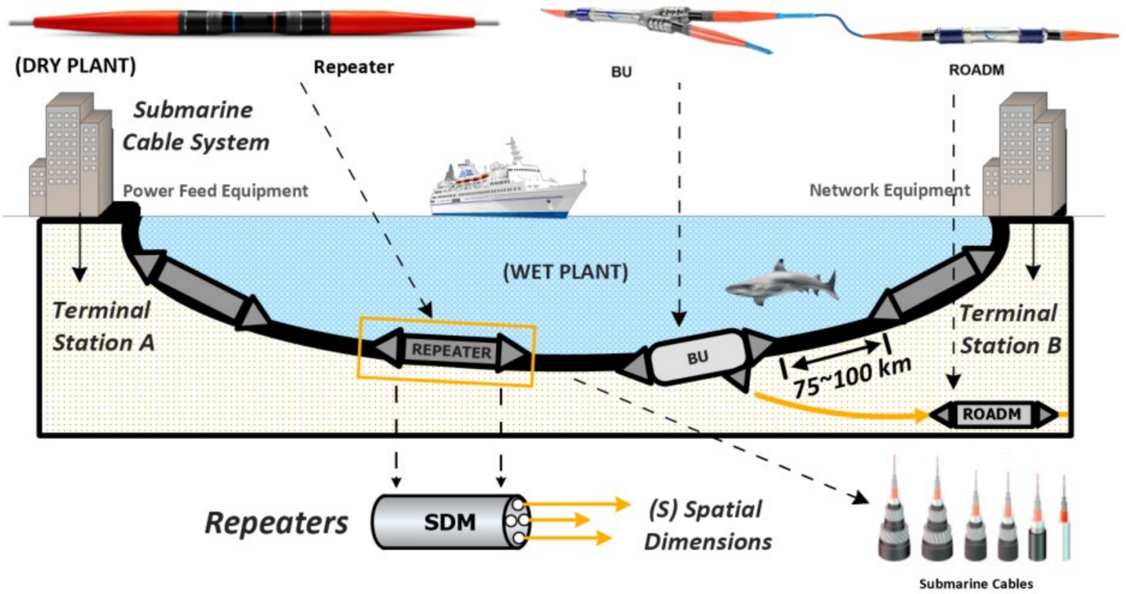


FIGURE 1.2: Underwater Optical Fiber Cable Archicture [19].

networks emerged as a complementary technology to optical fiber cables, enabling wireless data transmission over shorter distances.

Cellular mobile networks, also known as mobile broadband networks, utilize radio waves to establish wireless connections between mobile devices and cellular base stations. These base stations, typically located throughout populated areas, serve as relay points, routing data to and from the wired Internet backbone, largely composed of optical fiber cables. This hybrid approach allows for seamless data transfer between wired and wireless devices, enabling the ubiquitous connectivity relied upon today.

A pivotal role in the evolution of modern communication has been played by the development of cellular mobile networks. By providing wireless access to the vast trove of information available on the Internet, cellular networks have transformed the way people live, work, and interact with the world around them. From enabling instant messaging and social media interactions to facilitating remote work and e-commerce, cellular networks have become indispensable tools in daily life.

However, as mobile data usage continues to soar, the capacity of cellular networks is increasingly challenged. To meet the growing demand for bandwidth, network upgrades and the deployment of new technologies, such as 5G and beyond, are constantly being invested in by mobile network operators to improve network performance and provide a seamless user experience.

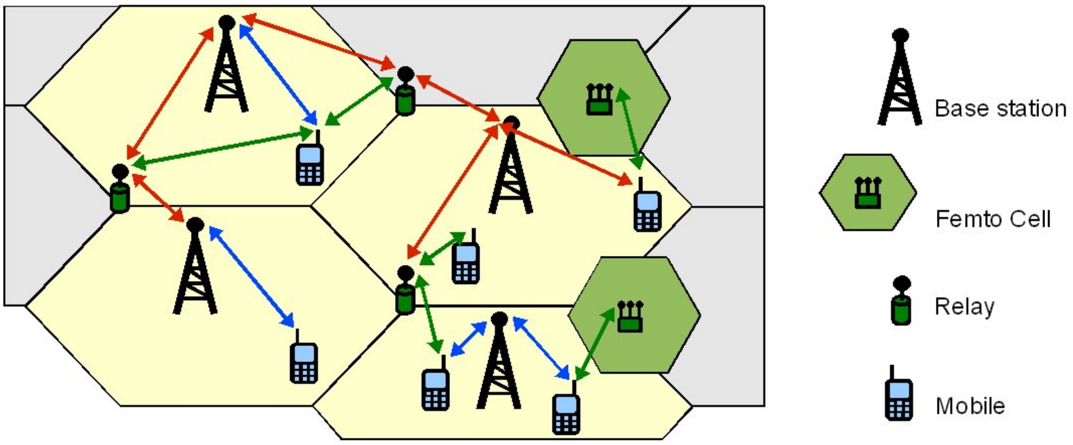


FIGURE 1.3: Landline Cellular Mobile Networks [20].

1.5 Landline Cellular Mobile Networks

A radio network spanning a vast geographic area is a cellular network, made up of cells, each containing a fixed transmitter/receiver known as a base station (BS). Radio coverage for a wider geographic area is provided when these cells are combined. Thus, communication is possible for cell phones even when moving between cell towers. Improved features, such as higher capacity, lower battery consumption, less interference from other signals, and wider geographic coverage area, are offered to subscribers by cellular networks compared to alternative solutions. Common cellular technologies include Global System for Mobile Communication (GSM), GPRS, and CDMA. The hierarchical structure supported by cellular network technology (PSTN) includes the mobile switching centre (MSC), base transceiver station (BTS), public switched telephone network (PSTN), and location registers. The cellular devices communicate directly with mobile phones through the BTS, which acts as a base station (BS) and routes calls to the destination BS controller. Interaction with the mobile switching centre (MSC) is facilitated by the base station controller (BSC) to interface with the PSTN, the visitor location register (VLR), and the home location register (HLR) for routing calls to various base station controllers. Information about the corresponding channels for mobile network signals is stored by mobile networks to track the position of their subscribers' mobile devices. Mobile devices are equipped with this information. Up to 30 miles of geographic coverage is provided by a typical cell site

[21]. Monitoring the signal level when a call is placed from a cellular phone is the responsibility of the BS. If the user moves out of the BS's geographic coverage area, the signal level may decrease. This can trigger a phenomenon known as "handover," in which a BS asks the MSC to hand over control to another BS receiving stronger signals, without informing the subscriber.

Environmental factors, such as a moving tower crane, overhead power lines, or the frequencies of other equipment, can often interfere with cellular networks. An overview of the basic landline cellular mobile network architecture is shown in Figure. 1.3.

1.5.1 Cellular Standards

Several standards are employed by mobile networks to facilitate the transfer of information between mobile devices. These standards are operated through complex radio systems. The subsequent text presents various cellular standards.

1.5.1.1 First Generation Cellular Networks: 1G

1G refers to the first generation of cellular mobile communication systems, which was the first system to utilize digital technology for communication. Introduced in the 1980s, 1G systems were primarily analog systems that utilized frequency division multiple access (FDMA) and time division multiple access (TDMA) to divide the available spectrum, allowing multiple users to communicate simultaneously.

Voice calls and text messaging were supported by 1G systems, but they were not capable of supporting data services such as the internet. Eventually, 1G systems were replaced by 2G (second generation) systems, which introduced the ability to transmit data and support internet connectivity.

1.5.1.2 Second Generation Cellular Networks: 2G

2G (second generation) was the first major advancement in cell phones 1G, and 2G differ in a number of ways. Still, one of the biggest differences is that the signal sent by the 1G system is analog and the signal sent by 2G networks is digital. It was primarily developed to provide a secure and reliable communication channel. As a result, CDMA and GSM were introduced. SMS and MMS, as well as a few other small data services, were available. Radiolinja (currently a member of Elisa Oyj) launched commercial 2G mobile networks in Finland in 1991. Multiplexing lets more than one user share a single channel so that 2G can be used. In the second generation, cell phones are not only used for voice calls but also for data transmissions.

Several fundamental services that remain integral to our communication today were introduced during the transition from 1G to 2G technology. These services include text messaging, internal roaming, conference calling, call waiting, and real-time billing. 2G can achieve speeds of up to 50 kbps with General Packet Radio Service (GPRS) or up to 1 Mbps with EDGE (Enhanced Data Rates for GSM Evolution).

Moreover, 2.5G and 2.75G were intermediate standards developed to bridge the gap between 2G and 3G networks before the introduction of 3G technology.

1.5.1.3 Third Generation Cellular Networks: 3G

The introduction of third-generation mobile communication systems in 2001 aimed to enhance voice and data capacity, facilitate a wider array of applications, and reduce the expenses associated with data transfer. The development of mobile telecommunication service and network standards adhering to the IMT-2000 specifications was undertaken by the International Telecommunication Union (ITU). The main network design for achieving 3G standards involved the utilization of the Universal Mobile Telecommunications System or Universal Mobile Telecommunications Service (UMTS) as a novel technology. By integrating the components of the 2G network with advanced technologies and protocols, this network facilitates significantly enhanced data transmission rates. According to the International Mobile Telecommunications-2000 (IMT-2000) standard, a genuine 3G network is characterized by a fixed speed of 2 Mbps and a mobile speed of 384 kbps. The maximum theoretical speed that may be achieved by HSPA+ is 21.6 Mbps. The progression from 2G to 3G, namely the advancements to 3.5G and 3.75G, can be attributed to the development of additional functionalities that ultimately facilitated the transition to 4G. The most recent iteration of mobile phones typically exhibits a high degree of backward compatibility, hence enabling the utilization of a 4G phone on a 3G or even 2G network. Nevertheless, it is important to note that devices operating on 3G and 2G networks are unable to establish communication on a 4G network.

1.5.1.4 Forth Generation Cellular Networks: 4G

Over the past decade, technological advances have made 4G technology possible. The technology provides clients with high-quality, fast data and voice connection. Its main goal is to increase security and lower costs for IP-based phone, data, multimedia, and Internet services.

Mobile Internet connectivity, IP-based telephony, gaming platforms, high-definition mobile television, video conferencing, three-dimensional television, and cloud computing are among the applications of 4G wireless communication technology.

Two important technologies—MIMO and OFDM—are used to attain the needed performance. WiMAX and LTE are the most popular 4G technologies.

LTE enhances the Universal Mobile Telecommunications System. Telstra is using 1800 MHz for LTE.

The 4G network can reach 1 Gbps while the user is stationary or walking and 100 Mbps when the device is moving. Thus, system congestion decreased as latency dropped from 300 ms to 100 ms.

Modern mobile devices can support earlier network generations, allowing a 4G phone to work on a 3G or 2G network. OFDM is a trustworthy sign of a legitimate fourth-generation (4G) service. This method divides the transmitted signal into narrow-band channels with different frequencies.

Table 1.1: Comparison of cellular technologies.

Generations	1G	2G	3G	4G	5G
Technology	Analog Voice	GSM	CDMA 2000	WI-FI	IPV6 LAN/WAN PAN
Multiplexing	FDMA	TDMA CDMA	CDMA	CDMA OFMA	CDMA BDMA
Year	1979	1991	2001	2009	2020
Use Cases	Dropped Calls Analog System Giant Cell Phones	Texting (SMS), MMS Conference Calls Long Distance Call Tracking	Cheap data transmission GPS, Web Browsing SD Video Streaming	HD Video Streaming Wearable Devices High Speed Applications	Internet of Things Cloud Computing Remote Surgical Robots
Frequency	30 KHz	1.8 GHz	1.6-2 GHz	2-8 GHz	3-30 GHz
Data rate	2.4-14.4 kbps	14.4-64 kbps	3.1-14.7 Mbps	100 Mbs-1 Gbps	1 Gbps and above
Range	N/A	50 miles	35 miles	10 miles	1,000 ft
Switching	Circuit	Circuit	Packet	Packet	Packet
Band type	Narrow	Narrow	Broadband	Ultra wide	Ultra wide
Handoff	Horizontal	Horizontal	Horizontal vertical	Horizontal	vertical
Features	Voice only	Multimedia features SIM introduced	Improved bandwidth and increased data rates High Security International Roaming	High speed, large capacity low bit cost Mobile networks that are global and scalable. Ad hoc and multi-hop networks are both possible.	Ultra reliable Extremely high Speed and low latency and many more

1.5.1.5 Fifth Generation Cellular Networks: 5G

5G, the latest mobile network technology, promises faster speeds, lower latency, and higher capacity, revolutionizing connectivity. It supports HD video streaming, VR/AR, and the Internet of Things, ushering in a new era of seamless and immersive experiences. 5G significantly enhances services and devices, fostering advancements in various industries. The technology utilizes low-band, mid-band, and high-band frequency bands, each tailored for specific characteristics and applications. As 5G networks are actively deployed, certain locations experience more extensive coverage, marking a transformative shift in global connectivity. The cellular industry created 5G to meet future software and service data requirements. Three new aspects distinguish 5G from prior networks. First, it generates tons of data. Cisco estimates that there were 8.6 billion mobile devices worldwide in 2017, and this number is expected to reach 29.3 billion by 2023, leading to crowded networks [22]. From 144 exabytes in 2017 to 924 exabytes in the early 2020s, data quantities are expanding rapidly. Second, QoS standards are enforced to ensure the proper operation of applications that require fast reaction times and significant data transfers. Third, the system must support smartphones, tablets, varied QoS requirements (such as data transfer and latency for certain apps), and network types such as trucks and trains. Three key new technologies in 5G increase network capacity for many user devices. First, mmWave communications use high-frequency bands (30 GHz to 300 GHz) and have at least 11 Gbps bandwidth. Since mmWave transmission range is narrower, user equipment can employ small cells to reduce interference. Last but not least, Massive MIMO (Multiple-Input Multiple-Output) uses several antennas to enable beamforming, which lowers interference and lets neighboring stations communicate simultaneously. Table. 1.1 briefly compares the five cellular generations.

1.6 Wireless Local Area Network (WLAN) Standards

In the subsequent paragraphs, an intellectual exploration is undertaken to unravel the complexities of WLAN standards, specifically focusing on WiFi 802.11. The objective is to thoroughly analyze and deconstruct the technical requirements and improvements associated with these standards. Examining the significant influence of these standards on the provision of Internet access during air travel, the transformative effects they have had on in-flight connectivity are observed. These standards have empowered passengers to effortlessly establish connections with the extensive realm of the digital sphere while traversing through the atmosphere. The study of the progression of WLAN standards and their incorporation into airborne networks allows for a more profound comprehension of the technological foundations that facilitate contemporary air travel encounters, distinguished by uninterrupted connectivity and limitless potential.

1.6.1 802.11 Standards

The 802.11 network comprises several standards, and these standards are maintained by the IEEE's LAN/MAN Standards Committee (IEEE 802), particularly IEEE 802.11. The IEEE 802.11 standard has undergone significant evolution over the years, and several new standards are currently being developed. The 802.11a standard is a wireless networking standard developed by the Institute of Electrical and Electronics Engineers (IEEE) in the 5 GHz frequency band. It was one of the first wireless networking standards developed by the IEEE and was published in 1999 as part of the 802.11 series of standards. The 802.11a standard is designed to operate in the 5 GHz frequency band and provides data transfer speeds of up to 54 megabits per second (Mbps). It is often used in corporate and enterprise environments because it can provide high-speed wireless networking over longer distances compared to other wireless standards that operate in the 2.4 GHz frequency band.

However, it is not as widely used as other standards such as 802.11b and 802.11g, which operate in the 2.4 GHz frequency band and are more commonly used in home and small office environments. The 802.11b standard was introduced together with 802.11a. It operates at a frequency of 2.4 GHz, while 802.11a operates at 5 GHz. 802.11b offers a theoretical maximum throughput of 11 megabits per second. This is a significant difference from 802.11a, which had higher frequencies but operated at 54 megabits per second. Although 802.11b is slower, it operates at a frequency of 2.4 GHz and has a wider range than 802.11a. A major challenge in developing an

802.11b network was the fact that other devices also operated at these frequencies. As of June 2003, the frequencies required for 802.11b were already being used by devices such as baby monitors, cordless phones, microwave ovens and others. The IEEE 802.11b standard has been updated to 802.11g. The radio frequency range used is also 2.4 GHz, and the transmission range is almost identical to 802.11a. The speed has been increased to about 54 megabits per second. 802.11g was intended as an upgrade for 802.11b and was backward compatible with it, but it was to be expected that the same frequency conflicts with the 2.4 GHz band would occur as with 802.11b. A revised standard, 802.11n, was introduced in October 2009 to replace 802.11 a, b, and g. 802.11n supports both the 2.4-GHz and 5-GHz bands and provides a throughput of about 600 megabits per second. MIMO technology is one method of achieving higher bandwidths.The 802.11n network can transmit many data streams simultaneously, which increases the overall throughput.

The 802.11ac standard is one of the latest standards for wireless technologies. It is an update to the 802.11n standard that provides an increase in throughput and additional features. This technology operates exclusively in the 5 GHz band. There is no 2.4 GHz option for 802.11ac. There is a much larger number of channels in the 5 GHz band. This allows us to increase the throughput of 802.11ac by using multiple channels.

With the modulation change, 802.11ac also became more efficient. A larger amount of data can now be sent in a shorter time. A number of improvements have been made compared to the MIMO technologies used in 802.11n. IEEE 802.11ac introduced multi-user MIMO technology. This allows to send eight different MIMO streams simultaneously to multiple devices over the network.

A generic overview of 802.11 standards is given in Table. 1.5.

1.7 Satellite Networks

Since their inception, satellite communications (SatComs) have been applied to numerous fields, such as media broadcasting, backhauling, and news gathering. Satellite communications are going through a change where the system is built around data services like broadband satellite communications. There are two primary reasons for this decision: a) rapid adoption of streaming media over linear media transmissions; and b) the pressing need to increase broadband availability in underserved areas (e.g., developing countries, air and sea transport, rural areas). For the fifth generation (5G) communication systems, integrating and combining various wired and wireless technologies is also a significant advancement. Therefore, SatComs are paving the way for seamless integration by focusing on specific use cases where their unique abilities can make things better.

1.7.1 Types of Satellites

There are many different types of satellites that are used for a wide range of purposes. Also, new types of satellites are being developed all the time to meet the changing needs of users. The next paragraphs discuss satellites according to their orbital altitudes. Low Earth orbits, medium Earth orbits, and high Earth orbits are the three basic orbits in which satellites move around the planet.

1.7.1.1 GEO Satellites

GEO satellites, orbit the Earth at an altitude of about 35,786 kilometers (22,236 miles), staying fixed relative to the Earth above the equator. Their synchronized orbit with Earth's rotation allows them to appear stationary in the sky, providing continuous coverage over large areas. GEO satellites are crucial for various purposes, including television, radio, telephone, internet, and weather forecasting, as well as military communication, navigation, and earth observation. They play a key role in providing broadband internet access to remote areas and mobile phone service to vehicles, while also enhancing navigation systems like GPS. In summary, GEO satellites' ability to stay in a fixed position over a broad area makes them essential for modern communication and navigation systems, facilitating global connectivity and seamless travel. Geostationary Earth Orbit (GEO) satellites offer several advantages. They can cover virtually every location on Earth with just three satellites. These satellites are stationary relative to a specific location on Earth, eliminating the need to adjust receiver or transmitter antenna locations. They are particularly suitable for broadcasting radio and television transmissions. With a lifespan of approximately 15 years, GEO satellites provide a long-term solution for continuous coverage of specific areas. They are not typically required to be decommissioned due to their substantial carbon footprints.

Furthermore, since GEO satellites have zero relative motion, they do not experience Doppler shifts [23]. However, GEO satellites also have several disadvantages. In the Earth's polar regions, larger antennas are necessary. Towering structures that block signals in urban areas and at low altitudes further from the equator can reduce the quality of transmission. The higher transmission power required can pose problems for battery-powered devices. These satellites are not compatible with small cell phones. One significant issue with voice and data connections is the severe delay of around 0.25 seconds in one direction [24]. The redundant transmission systems of fixed networks do not function effectively with GEO satellites.

Lastly, launching a GEO satellite into orbit can be extremely expensive. Despite these challenges, GEO satellites continue to play a crucial role in global communication networks.

Table 1.2: Different WiFi standards and their features

WiFi Standards	Year Issued	Remarks
802.11	1997	It is the original standard. It operates on 2.4GHz frequency band, with theoratical range of 66 feet and had a maximum bandwidth of 2 Mbps
802.11a	1999	On the 5GHz frequency band, it reached rates of up to 54 Mbps under ideal conditions.
802.11b	1999	Due to its lower development costs and wider adoption, the 2.4 GHz band has seen a surge in popularity over 802.11a. Maximum throughput of 11 Mbps has been attained.
802.11c	1998	It is related to the bridging of 802.11 wireless client devices (is now part of the 802.1d change).
802.11d	2001	This feature, also known as World-Wide Mode, enables clients to automatically adjust to the requirements of the country in which they are running, making things easier for nations that are not part of a huge domain.
802.11e	2005	Applications that are sensitive to latency, such as voice, data, and video, can benefit from the QoS capabilities that are given.
802.11F	2003	The Inter-Access Point Protocol allows communication between the 802.11 access points in the distribution system.
802.11g	2003	It combines the best of 802.11a/b to achieve 2.4 GHz speeds of up to 54 Mbps.
802.11h	2003	Originally developed for European regulations to solve interference issues with satellites and radars operating in the 5GHz band, they are now used worldwide.

Table 1.3: Different WiFi standards and their features (802.11i to 802.11y)

WiFi Standards	Year Issued	Remarks
802.11i	2004	It attempts to address WEP security flaws and improves wireless encryption for 802.11a/b/g networks by replacing short authentication and privacy with detailed security.
802.11j	2004	It is aimed at the Japanese market and includes specifications for using the 4.9 GHz and 5 GHz bands for outdoor, indoor, and mobile applications.
802.11k	2008	Improve the distribution of traffic within a WLAN.
802.11m	1999	Keep the 802.11 series and related documentation up to date.
802.11n	2009	It operates on the 2.4GHz and 5GHz bands and boosts speed to 600 Mbps.
802.11p	2010	Increases wireless access in vehicle environments (WAVE).
802.11r	2008	Designed to improve WLAN handoff speeds between access points.
802.11s	2011	Specifies how wireless devices can be linked to form a mesh network that can be used for both relatively fixed topologies and ad hoc connectivity networks.
802.11t	2008	Wireless Performance Prediction (WPP)
802.11u	2011	Boosts Internet connectivity with external networks.
802.11v	2011	Enhancements to wireless networking for client device administration and configuration.
802.11w	2009	Secures the management frame.
802.11y	2008	In the United States, it enables to operate in the 3650-3700 MHz bands.

Table 1.4: Different WiFi standards and their features (802.11ac to 802.11ba

WiFi Standards	Year Issued	Remarks
802.11ac	2013	It provides speeds of up to 1300 Mbps and supports 2.4GHz (through 802.11n technology) and 5GHz bands.
802.11ad	2012	On the 60GHz band, it can achieve extraordinarily fast data rates (up to 6.7Gbps).
802.11af	2014	Enables WLANs to function between 54 and 790 MHz in the TV white space band.
802.11ah	2016	Uses radio bands below 1GHz for decreased energy usage and greater range.
802.11ai	2016	Establishes mechanisms for fast initial link setup.
802.11aj	2018	By altering the physical and medium access control layers of 802.11ad, it makes possible to operate at Chinese millimeter wave frequencies (60 and 45 GHz).
802.11ak	2018	To improve the ability to use IEEE 802.11 media to provide internal links between bridged networks based on IEEE 802.1q.
802.11ax	2019	Provides quicker speeds, greater simultaneous device support, lower latency, enhanced security, and increased bandwidth.
802.11ay	2021	Provides a super-fast Wi-Fi (up to 176 Gbps) using high-frequency waves, but with shorter range and fewer compatible devices yet.
802.11az	2023	Time of Arrival based position estimation algorithm for WiFi clients.
802.11ba	2021	It aims to increase the battery life of sensors and devices particularly those used in IoT networks.

Table 1.5: Different WiFi standards and their features (802.11bb to 802.11be)

WiFi Standards	Year Issued	Remarks
802.11bb	2022	Explores extending connectivity range and improving performance in rural or underserved areas.
802.11be	Under Development	Will utilize 2.4, 5, and 6GHz bands and expand on 802.11ax to achieve exceptionally high throughput (EHT).

1.7.1.2 LEO (Low Earth Orbit) Satellites

Low Earth Orbit (LEO) satellites, typically positioned between 2 and 2000 kilometers above Earth, serve various purposes, including communications, military intelligence, espionage, and imaging applications[25]. They are favored for their shorter signal propagation latency and cost-effectiveness to launch, despite facing higher drag due to their denser orbital environment. The orbital velocity of a LEO satellite is significantly faster than that of a geosynchronous satellite. For instance, the International Space Station (ISS), which orbits the Earth at an altitude of about 400 kilometers, completes one orbit of the Earth every 93 minutes[26]. However, LEO satellites have a much shorter range for communicating with Earth and revolve around the Earth at a faster rate. Therefore, some applications require a network of satellites working together in a constellation [25].

LEO satellites offer several advantages. They transmit voice conversations at a rate of approximately 2,400 bits per second using modern compression techniques, ensuring clear and real-time voice communication [25]. Their proximity to Earth results in stronger signal strength and minimized time delays, making them practical for point-to-point communications. However, LEO satellites also have some disadvantages. Achieving global coverage requires a vast number of satellites, and their rapid movement significantly increases the complexity of the satellite system. They face the challenge of limited visibility at high altitudes, necessitating an additional link handover mechanism between satellites to ensure continuous communication. Objects in low-Earth orbit typically have a lifespan of 6 to 8 years [27]. Achieving seamless global connectivity involves complexities like transmitting data packets across satellite constellations, which may include data relay between satellites or multiple hops between base stations and satellites.

1.7.1.3 MEO (Medium Earth Orbit) Satellites

Medium Earth Orbit (MEO) satellites orbit the Earth between 6,000 and 20,000 kilometers above the surface. They have a broader coverage area and can be observed for two to eight hours longer than Low Earth Orbit (LEO) satellites. MEO satellites offer several advantages. They require only 12 satellites in an orbit of 10,000 km, which is more than a Geosynchronous Earth Orbit (GEO) system but significantly less than a LEO system [28].

These satellites move more slowly relative to the Earth's rotation, simplifying the system's design. MEO satellites offer a longer visibility time, larger coverage area, and a reduced need for frequent satellite switching compared to LEO networks.

This results in a more efficient satellite network with fewer satellites required for global coverage. Because MEO is pointed in a particular direction, it can cover a larger area, so it doesn't have to switch between satellites as often. However, MEO satellites also have some disadvantages. Due to the greater distance from Earth, the delay increases to approximately 70-80 milliseconds. The satellites need to have more power and special antennas to have a smaller footprint.

A comprehensive overview of various satellite types, including GEO, LEO, and MEO satellites, along with their respective advantages and disadvantages, is presented in Table 1.6.

TABLE 1.6: Different Satellite types and their features

Parameter	LEO	MEO	GEO
Satellite Height	500-1500 kms	5000-12000 kms	35,800 kms
Orbital Period	10-40 minutes	2-8 hours	24 hours
Number of Satellites	40-80	8-20	3
Satellite Life	Short	Long	Long
Number of Handoffs	High	Low	0
Gateway Cost	Very Expensive	Expensive	Cheaper
Propagation Losses	Least	Higher	Highest

1.7.2 Airborne Internet Access Through Satellites

Airborne Internet access through satellites refers to the use of satellites to provide Internet connectivity to aircraft while they are in flight. There are several different ways that this can be done, but the most common methods involve using either a satellite antenna mounted on the aircraft or a satellite-equipped router that is carried on board.

When using a satellite antenna, the aircraft communicates with a satellite in geostationary orbit, which then relays the signal to a ground station on the ground. From there, the signal is sent to the Internet via a terrestrial network. This allows passengers on the aircraft to access the Internet as if they were connected to a normal Wi-Fi network, with the satellite antenna providing the connection to the Internet.

Another option is to use a satellite-equipped router that is carried on board the aircraft. This router can communicate with a satellite in low Earth orbit (LEO), which provides a direct connection to the Internet. This type of system can be more efficient and faster than using a satellite antenna, but it requires a larger number of satellites to provide coverage.

Overall, using satellites to provide Internet access to aircraft can be a useful way to keep passengers connected while they are in flight, especially on long-haul flights or in areas where terrestrial Internet access is limited.

Because of its global reach, satellite-based Internet is said to be the most widely deployed Internet access mechanism. In the past, satellite-based broadband was the only solution to provide Internet worldwide. Today, satellite-based Internet is still the only solution when it comes to providing Internet to remote areas. Internet service can be provided by different types of satellites, but the most common ones are GEO and LEO satellites. The general advantages and disadvantages of the aforementioned satellites have already been mentioned in the previous section.

In the context of Internet provision, GEO and LEO satellites have distinct characteristics. GEO satellites, orbiting far from Earth (about 36000 km), offer a vast footprint, covering almost one-third of the planet. This provides a significant advantage over LEO, which orbits closer to Earth (500 to 1500 km) [29]. However, LEO has a smaller footprint, requiring a significant number of satellites and incurring high costs. The shorter orbital period of LEO results in lower delay but increases handover costs. Despite this, LEO struggles with limited Internet speed and suitability for bandwidth-intensive applications. Existing satellite solutions face challenges in latency, cost, and data rate, making them unsuitable for modern Internet applications with low latency requirements, such as remote monitoring and telemedicine. For instance, satellite links for Internet access in remote oceanic regions are costly and provide low bandwidth. Equipping an aircraft with the equipment needed for satellite Internet access costs about $500,000 [30–32]. In addition, monthly Internet bandwidth costs vary from $1,500 per month for a $128/128 kbps (i.e., speed of down/up connections) to $4,700 per month for a $2048/256 kbps connection [30, 31]. All of the above statistics explain that satellite-based Internet is a viable solution for urban and rural populations. However, it is still the only solution for remote areas.

1.8 Introduction to Routing and Its Importance in Airborne Communication Networks

The efficiency of airborne communication networks hinges significantly on the routing process, which is responsible for the effective transmission of data between nodes. Given the high mobility of nodes, the dynamic nature of the network topology, and the unique characteristics of the wireless medium, routing in airborne communication networks is a complex yet crucial task.

Routing algorithms play a pivotal role in managing these complexities. They can be broadly classified into proactive, reactive, and hybrid algorithms. Proactive algorithms maintain routing information in advance, while reactive algorithms discover routes on-demand. Hybrid algorithms attempt to combine the advantages of both proactive and reactive approaches.

Each category of these algorithms has its strengths and weaknesses, and their applicability depends on the specific requirements of the network. In this context, the routing algorithm proposed in this thesis aims to address some of the challenges associated with existing algorithms, thereby enhancing the performance of airborne communication networks. This section serves to underscore the importance of routing in airborne communication networks and sets the stage for the introduction of the proposed routing algorithm.

1.9 Research Objectives

This research is motivated by a defined set of objectives, strategically crafted to tackle the intricate challenges linked to ensuring optimal Internet access for aircraft navigating remote oceanic expanses. The primary research objectives encompass the following facets::

1.9.1 Objective 1: Development of Airborne Internet Provision Mechanism

The primary objective is to introduce a novel and cost-effective airborne Internet provision mechanism catering to users and aircraft flying over oceanic regions. Leveraging existing submarine optical fiber cables laid under the sea bed, particularly along major aerial routes such as the North Atlantic Corridor, the proposed solution establishes ground-to-air (G2A) wireless links.

These links directly connect to stationary ships stationed on the sea, serving as base stations for Internet provision. The data exchange is facilitated through the use of injectors/extractors, ensuring a seamless and efficient Internet delivery system to aircraft flying over oceans.

1.9.2 Objective 2: Quality of Service (QoS) Analysis

Conduct a comprehensive Quality of Service (QoS) analysis to evaluate the proposed airborne Internet provision mechanism. The analysis will specifically focus on essential QoS parameters such as end-to-end delay and packet delivery ratio. This objective aims to assess the reliability and efficiency of the proposed solution in delivering high-speed Internet access to airborne users.

1.9.3 Objective 3: Development of Cost-effective Reliable Transmission Service Algorithm

Design and present algorithms that ensure the reliability and scalability of data transmission within the proposed airborne Internet provision mechanism. These algorithms contribute to the overall efficiency of the routing process, providing a reliable transmission service for the Internet of Flying Things.

By achieving these research objectives, this study aims to provide a comprehensive solution to the challenges of airborne Internet access over oceanic regions, emphasizing cost-effectiveness, reliability, and quality of service parameters.

1.10 Thesis Contribution

The research contributions presented in this doctoral thesis can be listed in the following subsections.

1.10.1 Airborne Internet Provision Mechanism Through Submarine Optical Fiber Cables

To provide Internet access to aircraft flying over oceans, a new and comprehensive solution is presented. Ground-to-air (G2A) wireless links are established through a specialized infrastructure placed along the paths of existing undersea fiber optic cables and directly connected to them. This innovative approach, detailed further in Chapter 3, is backed by empirical data and references, ensuring the robustness and reliability of the claims made in this section. Compared to other communication methods reliant on satellites for data transmission, this method not only reduces costs but also significantly accelerates access times.

Unlike satellite-based alternatives, which may introduce delays and higher expenses, the G2A wireless system leverages existing optical fiber infrastructure for expedited and cost-effective data transfer. For a comprehensive understanding of this mechanism and its supporting data, please refer to Chapter 3 and Chapter 5.

1.10.2 QoS Analysis of the Proposed Solution

This thesis also includes a comprehensive QoS analysis of the proposed network infrastructure for its QoS provisioning based on some well-known QoS parameters such as delay and packet delivery ratio.

1.10.3 Cost-effective Reliable Transmission Service Algorithm for Internet of Flying Things

Algorithms for the reliability and scalability of the routing of data utilizing the proposed solution are also presented.

1.11 Applications of the Proposed Research

There are numerous applications of airborne Internet access via underwater optical fiber cable. Some of the notable applications are mentioned in the following lines.

1.11.1 Telemedicine and Air Ambulance

Telemedicine is becoming a common trend in the present medical system. The world is opting for remote surgeries.

To take advantage of telemedicine and improve air ambulance facilities, a fast and reliable Internet connection is a must. Since the proposed research overcomes the bottlenecks of low data rates and longer delays, the facility of telemedicine in an air ambulance and regular commercial flights can be timely entertained. In commercial flights, in-flight medical emergencies (IMEs) are not uncommon.

The lack of medical assistance makes it even more problematic. Nearly 44,000 IMEs occur worldwide each year. Syncope (37% of cases), breathing difficulties (12%), vomiting or nausea (9%), and cardiovascular abnormalities (7%) are the most common IMEs. In almost 45% of all flights, the crew has to provide medical assistance. Overall, 25.8% of IME patients were hospitalized by Emergency medical service (EMS) personnel, 8.6% were hospitalized, and 0.3% died [33, 34]. In-flight medical care is essential for a variety of reasons. Each year, approximately 1000 lives are lost in commercial flights. In addition, more than 11% of IMEs result in a flight being diverted due to an emergency. Diversion is costly as an unexpected landing of a diverted flight can cost between $70,000 and $230,000 [35]. Telemedicine is a critical use case when all of the above data is considered. If timely medical treatment is offered in IME cases, lives can be saved. For example, defibrillation within 3 to 5 minutes of an incident can result in a 50% to 70% survival rate [36].

1.11.2 Live Blackbox

A ”black box” records crucial data from an aircraft, vehicle, or system, aiding in understanding events or monitoring performance [37]. A ”live black box” implies real-time data transmission instead of storage for later analysis. In-flight Internet with reliable high bandwidth is essential for transmitting vital black box data to ground stations [38]. A transmission rate of 25 Mbps is needed for all 88 parameters. Underwater Optical Fiber Cables (UOFC) provide the only viable option for live black box implementation for ocean-flying aircraft. UOFC can process data from four aircraft per Oceanic Station simultaneously, enhancing efficiency, saving time, and reducing costs associated with accidents. This approach minimizes reliance on expensive satellite-based communication, preventing delays and ensuring timely data transmission and basic calculations during flight over the ocean.

1.11.3 Internet of Me

There has been research in the field of brain-computer interfaces (BCIs) that aims to develop technology that can allow a person’s brain to directly control a computer or other device. BCIs work by detecting and interpreting brain signals, such as electrical activity or brain waves, and translating them into commands that can be used to control a device.

While BCIs have the potential to offer many benefits, such as allowing people with disabilities to communicate or control devices, they are still in the early stages of development, and many challenges need to be addressed before they can be widely used. The concept of putting one's brain and body online is called the Internet of Me (IoM) [39]. IoM can be used in a variety of applications, such as a live black box scenario that allows us to track the pilot's brain using video electroencephalography (V-EEG) and neurofeedback, which is currently particularly useful in the event of an accident. Neurofeedback is a form of real-time brain visualization that can be used to track attention, cognitive workload, and confusion [40]. When brain-state data and other relevant information is readily available, it becomes much easier for the relevant authorities to take the necessary actions and provide feedback and instructions to pilots and crew members. This is because they have access to a wealth of data that can help them understand what is happening and make informed decisions. In situations where this information is not readily available, it can be more difficult for authorities to respond effectively and provide the appropriate instructions. Therefore, access to live brain state data and other real-time information can be invaluable in ensuring that appropriate actions are taken and that pilots and crew members are able to safely handle any challenges they may face. In addition, in the event of an accident, investigative teams can better determine the reason for the crash by examining the IoM data and brain state at the time of the incident. Moreover, they not only have data from the black box, but also about the pilot's emotions or state of mind at the time of the accident. To establish a connection between the brain and the computer, a high data rate is required. For example, remote EEG monitoring with V-EEG requires a data rate of 26 Mbps [41].

1.11.4 Cloud Computing

Handheld devices, such as smartphones and tablets, have become an integral part of modern life, offering a wide range of functions and capabilities that make them incredibly useful and convenient. These devices are equipped with a variety of sensors, processors, and other hardware components that allow them to perform a wide range of tasks, such as making phone calls, sending text messages, accessing the Internet, playing games, and much more. In addition to the hardware, handheld devices are also supported by a vast ecosystem of software applications, or apps, that can be downloaded from app stores or other online platforms. These apps allow users to customize their devices and extend their functionality even further, adding new features and capabilities that can make them even more useful and resourceful. Overall, the increasing capabilities of handheld devices have made them an essential part of modern life, and they continue to evolve and improve with new advancements in technology. On the other hand, however, modern applications and services require more resources, sometimes even more than are available on mobile devices. To tackle this problem, mobile devices are shifting tasks to a resource-rich entity called cloud data centers. The cloud has virtually unlimited resources, but it can only be accessed via the Internet. For commercial flights, satellite-based Internet connectivity belies the true potential of cloud computing. To realize the full potential of cloud computing, stable and fast Internet access is a must. It is worth noting that most of the very popular applications like Gmail, YouTube, Facebook, Netflix, etc. that are used extensively everywhere (including air travel) are all cloud-based applications.

1.11.5 Online Entertainment

The significance of E-entertainment in the Internet landscape is undeniable, with cloud gaming emerging as a prominent trend. It offers a cost-effective alternative to traditional gaming models by eliminating the need for expensive hardware and game installations, aligning with the growth of internet and mobile gaming. Despite its advantages, cloud gaming faces challenges related to user experience due to the geographical distance of cloud data centers accessed only via satellite, resulting in significant delays for end-users.

High bandwidth speeds are crucial for various e-entertainment activities, such as MMOGs, on-demand movies, and online browsing [42]. For instance, a 10 Mbps data rate is necessary for seamless simultaneous activities like video conferencing, on-demand movie streaming, and online browsing. Advanced internet games like Thumper and Tomb Raider demand even higher speeds, with 23.32 and 28.97 Mbps, respectively. Family-oriented internet use, encompassing movie streaming, video conferencing, and web surfing simultaneously, requires at least 10 Mbps [42].

Underwater Optical Fiber Cables (UOFC) emerge as a solution to enhance data rates for online gaming and other e-entertainment applications, addressing delayed graphics playback. This technological advancement not only minimizes time delays but also significantly improves Quality of Service (QoS), ensuring a more enjoyable and efficient e-entertainment experience.

1.11.6 Telepresence

Telepresence is a high-quality video conferencing technology that feels like you are talking and interacting with others in the same room, even if they are in a different location or on the other side of the globe [43]. With this technology, point-to-point calls can be made where one telepresence unit calls another unit directly. In multipoint calls, up to 20 telepresence units can communicate simultaneously. Telepresence is different and much better than traditional video conferencing because it offers dynamic features such as focus adjustment and a wide view of the other side through camera control, where the camera can be panned, zoomed, tilted, and presets (such as turning on the camera, etc.) can be made.

On a long plane, people have to attend different meetings. Doctors and other experts also need to observe the situation from a distance with high-quality video.

In the current Covid 19 pandemic, the need for telepresence is becoming greater than ever. Telepresence is imperative to enable a high-quality experience in various domains like online meetings/conferences, distance learning, e-health, telemedicine, etc. High data rates are required to enable such high-quality video and audio experience. For example, the Cisco telepresence SX20 can operate at 10Mbps. Telemedicine also requires 24Mbps with a latency of 50ms for high definition telepresence; this is typically critical for remote monitoring (e.g., tuberculosis treatment through directly observed video therapy, speech pathology detection, etc.).

1.12 List of Publications

1. Najmul Hassan, Noor. M. Khan, ”Cost-effective reliable transmission service for Internet of Flying Things.” *International Journal of Distributed Sensor Networks.*, vol. 17, no. 6, pp. 1-13, June 2021.

2. Syed. J. Nawaz, Noor. M. Khan, Muhammad. I. Tiwana, Najmul Hassan, Syed. I. Shah, "Airborne Internet access through submarine optical fiber cables", *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 1, pp. 167–177, January 2015.

3. Najmul Hassan, Noor. M. Khan, Ghufran Ahmed, Rodica Ramer, "Real-time gradient cost establishment (RT-GRACE) for an energy-aware routing in wireless sensor networks", *IEEE eighth international conference on Intelligent sensors, sensor networks, and information processing.*, pp. 54–59, June 2013, Melbourne, VIC, Australia.

1.13 Thesis Organization

This thesis is organized as follows: Chapter 2 examines the current state of the art in aerial Internet delivery. Also, it focuses on reviewing other relevant models and showing how our approach differs from others.

Chapter 3 introduces our proposed architecture for delivering airborne Internet over underwater optical fiber cables. The chapter begins with a description of the communication network design. Subsequently, the architectural model supporting our proposed solution is detailed, accompanied by an overview of the data flow within this architecture. Chapter 4 entails an analysis of handover performance in high-mobility scenarios, taking into account factors such as aircraft velocity, movement direction, and propagation environment. This analysis plays a crucial role in optimizing radio cell planning and minimizing delays in traffic changeovers constrained by Quality of Service (QoS). In Chapter 5, a comprehensive analysis of the QoS of the proposed network infrastructure is conducted, assessing key parameters such as delay and packet delivery ratio. The Airborne Ad-hoc Routing Algorithm (AARA), developed as part of our solution, is compared to the geographic forwarding strategy (GLSR) through extensive simulations.

Evaluation is based on end-to-end delay and packet delivery ratio, involving approximation, mathematical modeling, and simulation to validate the results. Whereas, in Chapter 6, the proposed solution is extended to accommodate real-time applications of unmanned aerial vehicles (UAVs). Building upon these foundations, Chapter 7, Conclusion and Future Work offers insights into potential applications and future extensions of the airborne Internet access solution proposed.

Chapter 2

Literature Survey, Gap Analysis and Problem Formulation

This chapter presents a literature survey, gap analysis, and problem formulation related to the work done in the thesis. In Section 2.1, a detailed literature review is presented. Section 2.2 and 2.3 focus on the gap analysis and problem statement respectively, while Section 2.4 describes the research methodology. Finally, Section 2.5 explores current advancements in the field of airborne Internet access and their impact on the proposed research.

2.1 Literature Survey

Providing smooth Internet connectivity to the aeroplane is a difficult undertaking. Various techniques for providing Internet, navigation, and security services to aircraft via ground stations or satellites have been proposed in the literature in order to fulfil the objective of giving Internet access in aircraft. [44–53].

Commercial flights are currently handled by satellites in most cases. Geosynchronous Equatorial Orbit (GEO) satellites are used to connect users to the Internet from the air. GEO satellites orbit at an altitude of over 36000 kilometres above the Earth's surface. Because of their great distance from the Earth's surface, they can provide global coverage [54]. Satellite links could provide global coverage, but on the other hand, the distance of GEO satellites from the Earth's surface makes them an impractical solution for Internet coverage, especially for real-time applications. Satellite transmission has an average end-to-end delay of more than 600 milliseconds, which only allows delay-insensitive activities such as web browsing [55]. Moreover, many existing and future real-time applications and services cannot tolerate such a delay (remote operations, etc.). In addition, cost is a critical factor, as it costs nearly $500,000 to equip a single aircraft with this technology. In addition, according to [56], the monthly data transfer cost for satellite communication is around $200 to $3000. Such a significant end-to-end delay and associated cost limit the use of the full potential of mobile devices and results in insufficient use of valuable resources (e.g., memory and processor) throughout the flight, which may last several hours (for example, the longest flight between Doha, Qatar, and Auckland, New Zealand, is 17 hours and 30 minutes) [57]. In [53], a network architecture has been developed for highly-dynamic aerial networks, along with simulation results that address several challenges of highly dynamic environments, such as short transmission times and limited connectivity caused by high-speed aircraft mobility. A Wireless Sensor Network (WSN) that is based on floating nodes and utilizes a self-configuring and self-organizing routing approach is proposed in [30] as a means of providing Internet connectivity to ships located in far-flung areas of the ocean. A multi-hop ad hoc data network for aircraft is suggested in [49]. This technique allows an aircraft to broadcast both its position and the locations of its nearby neighbors. The system employs both time division multiple access and space division multiple access techniques for communication. However, for this method to effectively convey data, it requires the optimum number of planes in the air at all times, which can be difficult to achieve depending on the time of day. For regularly updating ground traffic controllers on aircraft's location, [50] presents an aeronautical ad-hoc network for high aviation traffic in maritime places. Several methods have been described in the literature for providing Internet to aircraft flying across the globe. The majority of the proposed techniques continue to rely on satellite links as the backhaul channel, although a few are satellite-free. Mobile ad hoc and mesh network topologies underpin the majority of satellite-free techniques. Consequently, the methods of providing Internet access through aircraft can be categorized into three broad groups.: (1) Satellite Based Approaches (2) Ground-to-aircraft/UAV approaches. (3) Hybrid approaches.

2.1.1 Satellite-Based Solutions

Satellite-based aerial Internet access is one of the earlier techniques introduced in the late 90's [58]. Most of the airborne Internet delivery solutions deployed today are satellite-based. The concept of satellite-based airborne Internet delivery is shown in Figure. 2.1. There are a number of solutions that discuss this approach for airborne Internet delivery. Some of the notable solutions are described in the following lines.

The authors in [44] suggest a framework for providing Internet to passengers as well as for making it easier to provide services for an aircraft's cabin. However, the addition of the satellite link and the intricacy of the design make this approach both slow and inefficient in terms of cost. To better provide Internet services to the aeroplane, a system that incorporates both ground stations and satellite stations is suggested in [45]. By suggesting a cluster-based wireless ad hoc network approach, it is demonstrated that the expenses of airplanes' communication links with satellite and ground stations can be decreased. The cluster head uses satellite links to provide Internet material to the aircraft connected to this cluster. It also demonstrated a massive cache that stores all content retrieved from the Internet and can be used for future requests for the same content. Khan presented a satellite-based technology for providing Internet to cars and airplanes [59]. However, instead of GEO satellites, this method uses Low Earth Orbit (LEO) satellites. Since LEO satellites orbit the globe at a much lower altitude than GEO satellites, the scalability of the solution is limited. Reid *et al.* proposed an airborne Internet solution, but it focuses primarily on terrestrial users [60].

[60] provides an explanation for the distribution and routing of data within the aircraft. Data routing within an aeroplane is represented using a system based on the concept of a mobile router. Satellites are used to deliver the Internet, and they are said to deliver high-bandwidth Internet connectivity with good reliability. It lessens the quantity of handovers as well. The drawback of this satellite link is, however, its high price, which cancels out the advantages of this strategy. The authors of [46] described a method for uploading real-time flight-critical data to ground station servers through a satellite link to allow ground stations to monitor flight status. In [47], internet provision, and associated security concerns for aeroplanes are covered.

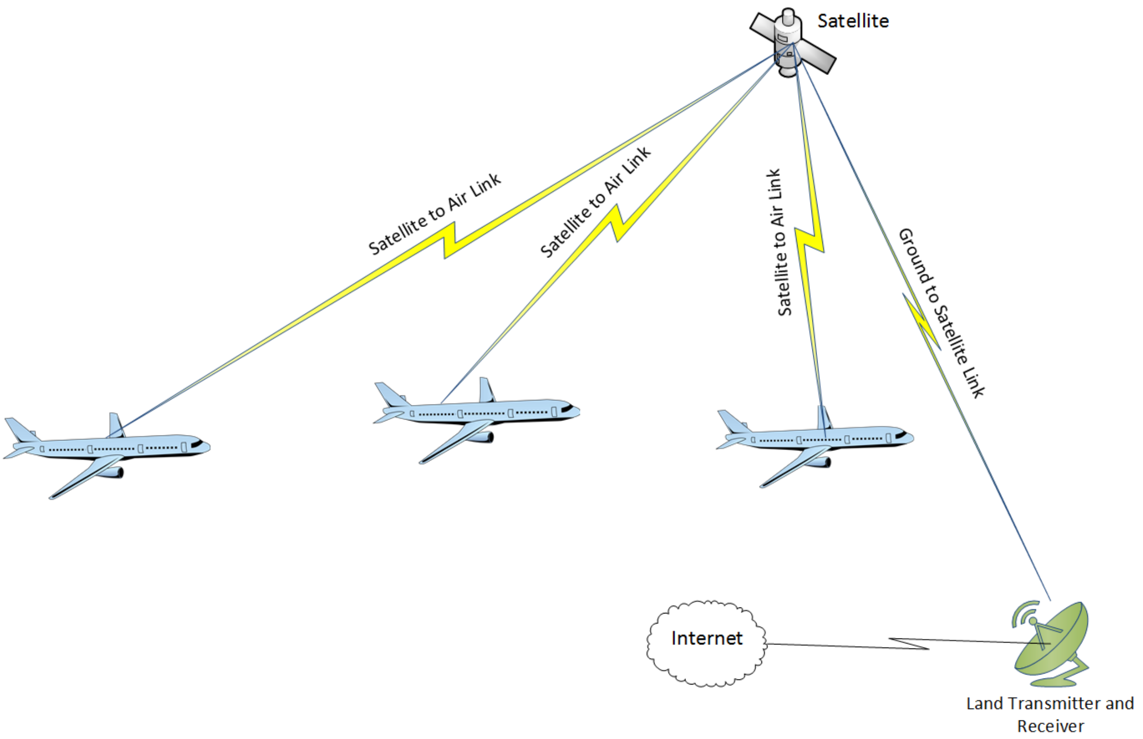


FIGURE 2.1: Airborne Internet provision through satellite only

To improve throughput and reduce latency, Vey *et al.* developed an ad hoc network for aircraft flying over the sea [61]. However, since this system depends on network density, it loses effectiveness when there are fewer aircraft in the ad hoc network. Jalali *et al.* investigated a similar strategy for providing Internet to aircraft using satellite and ground-to-air links [62]. The authors also demonstrated a network of flying aircraft. However, satellite links can only be used when flying over isolated areas such as the ocean or desert. Although satellite-based techniques provide global coverage, satellite is not a viable option for Internet connectivity due to cost and delay. Therefore, some alternative Internet transmission methods have been proposed in the literature.

2.1.2 Ground-to-Air Based Solutions

Ground-to-air connectivity (G2A) uses ground-based cell towers to provide Internet service to aircraft passengers. The initial deployment of gogo Internet was based solely on G2A connections. They used their cell towers along flight routes in the US. Although this is a relatively new concept for providing high-speed Internet, there are two major drawbacks to this approach. First, this solution is only suitable for flights

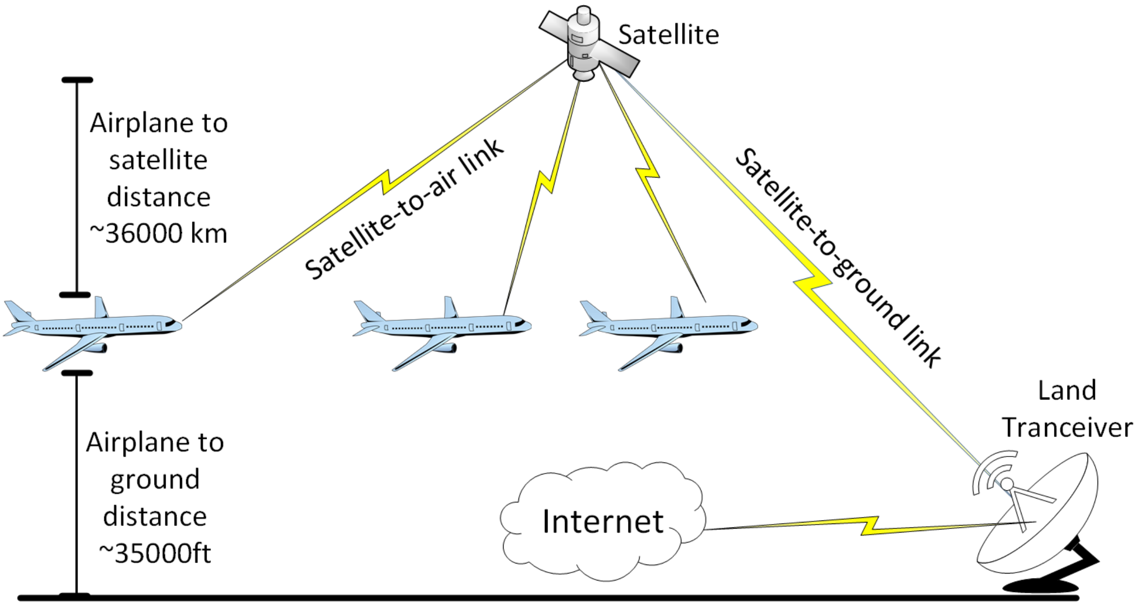


Figure 2.2: Airborne Internet provision through Ground Station only

that fly over cell towers. Thus, it is not a scalable solution. Second, the approach based on the G2A link is the least suitable for providing Internet to aircraft flying over oceans and even over remote ground areas. Figure. 2.2 shows the G2A link-based approach to providing Internet to flying aircraft. In the literature, there are some solutions that use ground stations to provide Internet to aircraft. Tadayon *et al.* developed a ground station-based method for delivering Internet in the air [63]. To bring Internet to aircraft, this approach is based on LTE (Long-Term Evolution). In [64], Gupta and Aggarwal propose a similar technique. In this solution, a gateway aircraft is connected to a ground station, and the gateway aircraft is responsible for providing Internet to the other flights within its range. This technique only works when an aircraft is in the vicinity of the ground station. In addition, the proposed approach would not be practical in areas with less intensive air traffic.

All of the above techniques for providing airborne Internet are limited to providing Internet to flights flying over land. However, there are certain ground-to-air link based technologies that provide Internet connectivity to passengers aboard aircraft flying over water.

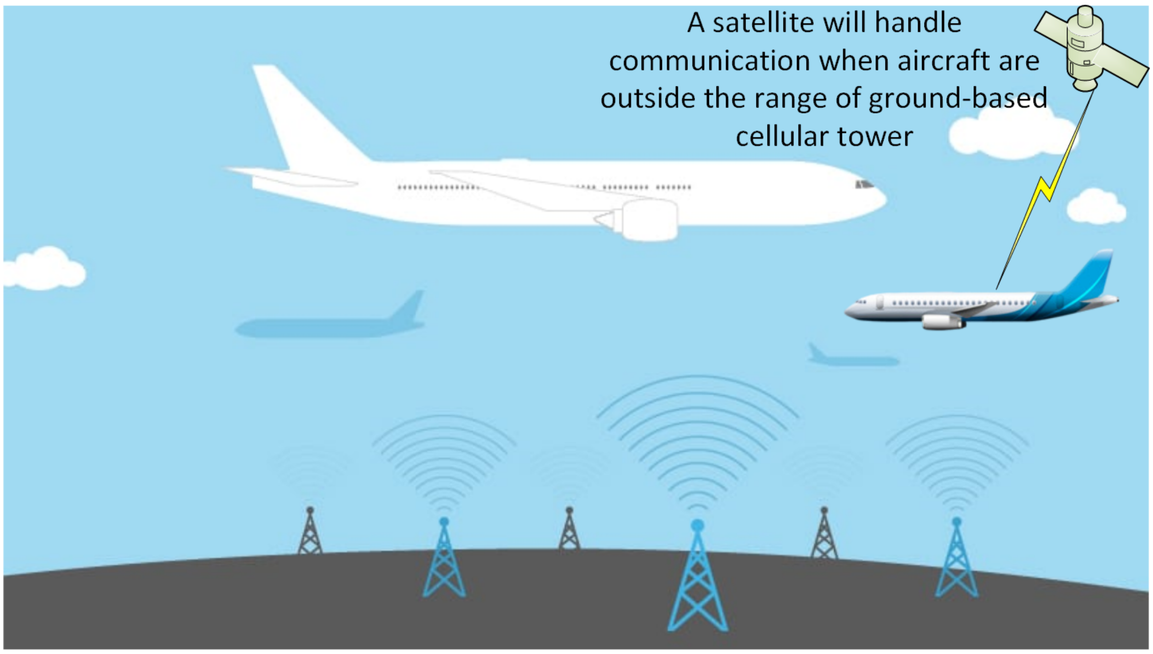


FIGURE 2.3: Gogo Internet: Airborne Internet access through ground based cellular towers.

2.1.3 Hybrid Solutions

In these approaches, ground-to-air link and satellite approach are used to provide Internet. Normally directional antennas and beam forming is used on land stations i.e. when a plane is flying over the land and satellite is used for Internet connectivity when the plane is out of range from land station or specifically when it is flying over the ocean.

Figure. 2.3 explains the operation of gogo Internet, which uses ground-based cellular stations as Internet providers for airborne users. Cell towers can only provide Internet to aircraft that are within the transmission range of the respective cell tower. If, on the other hand, the aircraft is outside the range of the cell tower, the satellite takes over communications. Gogo is an example of a hybrid solution. Various variants of hybrid approach have been utilized by a large number of authors so far [65, 66].

In addition to direct connection with ground stations and use of satellites, [65] introduces a new category of networks known as aeronautical ad hoc networks (AANET) by extending the network design to allow multihop ad hoc networks between aircraft. A new ad hoc network has been unveiled that allows commercial aircraft in the sky to exchange data and surf the Internet together. When an aircraft first connects to the AANET, it can download information from the Internet, either indirectly via a satellite or directly from the ground. The data can then be cached and shared with other nearby aircraft using ad hoc networking techniques to dynamically establish paths with one or more hops to the requesting aircraft. These paths can consist of a single hop or multiple hops. Lynch *et al.* presented a hybrid approach for transmitting online content to aircraft using both satellite and ground-to-air communications [67]. However, in the absence of a ground station, aircraft flying over the ocean are not considered in this solution. In [51], a network model was presented that deploys mesh networks between a fixed number of ground stations and an arbitrary number of aircraft to provide Internet to aircraft flying over oceans. Aircraft within range of ground stations in coastal areas can access the Internet via an air-to-ground (A2G) communications link. By using the air-to-air communications link (A2A) of a mesh network, distant aircraft can now access the Internet. A routing technique called GLSR (Geographic Load Share Routine) is also proposed, which optimally utilises the capacity of the A2G link by exploiting the aircraft's position and buffer size. In this technique, the traffic of all aircraft in the ocean region is routed through the A2G communication link of the coastal ground stations, with the aircraft flying within their range over the coastal areas. Due to the high mobility of aircraft, the life of such links is typically very short, leading to an increased risk of service degradation. In [52], a routing protocol for aircraft with localized geographic load balancing technique is proposed. It manages network congestion while considering link scheduling constraints by using highly directional antennas. Comparison of some notable existing solution is shown in Table. 2.4.

2.1.4 Existing Operational Solutions

Airborne Internet access has been in use since early 2000's [68].

Currently there are a number of solutions that provide in-flight Internet. Different airlines use Internet services of different Internet providers.

It is worth noting that some flights use Internet services of more than one Internet service provider, depending on their needs and coverage in different parts of the world. Some of the well-known in-flight Internet providers are listed in the following lines.

2.1.4.1 Gogo®

Gogo is a company that provides in-flight internet and entertainment services to airlines. Gogo's in-flight internet service allows passengers to connect to the internet while on a plane, using either their own device or a device provided by the airline. Gogo's service is available on many commercial airlines and is provided using a combination of satellite and A2G technologies. The company also offers in-flight entertainment services, such as movies, TV shows, and games, which can be accessed using a personal device or in-seat screens. Gogo's services are designed to enhance the travel experience for passengers and to allow them to stay connected while in the air. As mentioned in the above lines, Gogo® is one of the notable in-flight Internet providers Initially, Gogo was deployed only in the U.S. Gogo provide Internet to aircraft flying over the U.S. via ground-based cellular towers. Gogo's G2A infrastructure used to provide 3G Internet at a data rate of nearly 9Mbps per aircraft. Currently, Gogo is expanding its services to other parts of the world. Both satellites and ground-based cell towers are being used for Internet connectivity. Nearly 20 airlines use Gogo Internet on their flights. These airlines include Qatar Airways, Virgin Atlantic, United Airlines, Vietnam Airlines, Virgin America, Virgin Australia, Level, LATAM, KLM, JTA, Japan Airlines, Delta Air Lines, Iberia, British Airways, Cathay Pacific, GOL Airlines, American Airlines, Air France, Alaska Airlines, Air Canada and Aeromexico.

2.1.4.2 Inmarsat

Inmarsat is one of the leading satellite-based Internet providers. As part of its initial offerings, Inmarsat began providing voice and slow data services. Currently, the company operates a mobile satellite system that provides worldwide spotbeam operations. The company is also gaining popularity in the airborne broadband Internet provision. The Inmarsat Internet system is already installed on 10,000 aircraft.

With the launch of the Global Express Network (also known as GX Aviation), Inmarsat has taken a step towards meeting the capacity needs for future Internet connectivity in the aviation industry. It is worth noting that GX Aviation uses a constellation of five satellites dedicated to in-flight Internet. Inmarsat provides Internet to aircraft using multiple satellites, including Inmarsat-3, Inmarsat-4, Inmarsat-5 Gx, Alpha L-band, and EuropaSat S-band.

Several airlines use Inmarsat's Internet on their flights. These airlines include Emirates, Lufthansa, Qatar Airways, Singapore Airlines, Air New Zealand, Virgin Atlantic, AirAsia, Saudia, and China Airlines.

2.1.4.3 OnAir

One satellite-only airborne Internet provider is OnAir. OnAir allows passengers to use laptops, tablets, and smartphones to browse the Internet. OnAir's global connectivity relies on GEO satellites, hence, it has cost and delays issues. OnAir offers limited in-flight cell phone service with cellular telephone, text messaging, and Internet access. Passengers can use their phones to call, text, email, and browse the Internet. OnAir uses Inmarsat's L-band SwiftBroadband service, which caps bandwidth at 864 kbps.

Qatar Airways, Oman Air, All Nippon Airways, ANA, Cebu Pacific Air, Egypt Air, Emirates, Garuda Indonesia, Hong Kong Airlines, Iberia, Libyan Airlines, Philippine Airlines (PAL), Saudia, Singapore Airlines, TAM, TAP Portugal, and THAI Airways use OnAir for airborne Internet.

2.1.4.4 Panasonic Avionics

Panasonic Avionics is a provider of in-flight entertainment systems that include music, video-on-demand (television and movie channels), in-flight shopping, telephone service, e-mail, and video games. Panasonic Avionics supplies aircraft manufacturers Boeing, Airbus, and Bombardier with electronic components.

Panasonic Avionics offers an in-flight Internet access option based on satellite technology. Several airlines use Panasonic Avionics' Internet on their flights.

These airlines include Aer Lingu, Air Berlin, Gulf Air, Lufthansa, Malindo Air, SAS, Singapore Airlines, Transaero, Turkish Airlines, and WestJet.

2.1.4.5 Row44

Row 44, Inc. is part of the Global Eagle Entertainment Group, a company that offers Wi-Fi and entertainment content to commercial airlines via satellite that is distributed by a network of companies located around the world. Using Row 44, airlines all over the world can give their passengers access to a high-speed Internet connection, premium entertainment like live TV and streaming video-on-demand, and local activities that can be booked while in flight and streamed straight to their Wi-Fi-enabled devices.

With the help of its airline partners, Row 44 runs a fleet of nearly 500 high-speed planes that can connect to Wi-Fi in a number of ways, both on land and in the air. With the use of Ku-band satellite technology, passengers on the Row 44 platform can connect to the Internet through a wireless connection. A few airlines use Row44 as their Internet service provider, including Icelandair and Norwegian, and they are only a few of them.

2.1.4.6 AeroMobile

AeroMobile is a mobile service provider for the aviation industry based in the United Kingdom. It uses both ground stations and satellites to provide Internet to passengers on board. AeroMobile provides services that allow air travelers to make calls, text, and use mobile data while being on-board. Cell phones can only be used on flights that use the AeroMobile Network. To ensure that cell phones can be used safely on board, specific hardware has been installed in these aircraft.AeroMobile operates like any other private cellular network. If the passenger's home cellular provider has a roaming agreement with AeroMobile, they can use their phone just as they would when roaming in another country. The cell phone may turn on after an announcement from the cabin crew to let you know when to turn on your phone and use the service. Usually, this may be the case at 6000 meters altitude. The network is available throughout the flight, but passengers must turn off their phones during landing and takeoff. Several airlines use AeroMobile as an Inflight Internet service provider including, Aer Lingus, Air Belgium, Asiana Airlines, Biman Bangladesh Airlines, Cathay Pacific, EgyptAir, Emirates, Etihad Airways, EVA Air, Kuwait Airways, Lufthansa, Malaysia Airlines, SAS Scandinavian Airlines, Singapore Airlines, Swiss International Air Lines, TAP Air Portugal, Turkish Airlines, Uzbekistan Airways.

Table 2.1: Comparison of Notable Existing Commercialise Services (Cont)

Provider	Airlines	Technology	Data Rate
Gogo	Qatar Airways, Virgin Atlantic, United Airlines, Vietnam Airlines Virgin America, Virgin Australia, LATAM, KLM, JTA,Japan Airlines Delta Air Lines, Iberia, British Airways,Cathay Pacific, GOL American Airlines, Air France, Alaska Airlines, Air Canada, Aeromexico	Satellite and G2A	Nearly 9Mbps
Inmarsat	Emirates, Lufthansa, Qatar Airways, Singapore Airlines Air New Zealand, Virgin Atlantic, AirAsia, Saudia, China Airlines	Satellite	Upto 50Mbps
OnAir	Qatar Airways, Oman Air, All Nippon Airways, ANA Cebu Pacific Air, Egypt Air, Emirates, Garuda Indonesia HongKong Airlines, Iberia, Libyan Airlines, Philippine Airlines Saudia, Singapore Airlines, TAM, TAP Portugal, THAI Airways	Satellite	864 kbps
Panasonic Avionics	Aer Lingu, Air Berlin, Gulf Air, Lufthansa, Malindo Air, SAS Singapore Airlines, Transaero, Turkish Airlines, WestJet.	Satellite	Varies

Table 2.2: Comparison of Notable Existing Commercialize Services

Provider	Airlines	Technology	Data Rate
Row44	Southwest Airlines, Icelandair and Norwegian	Satellite	Varies
AeroMobile	Aer Lingus, Air Belgium, Asiana Airlines, Biman Bangladesh Airlines Cathay Pacific, EgyptAir, Emirates, Etihad Airways, EVA Air Kuwait Airways, Lufthansa, Malaysia Airlines, SAS Scandinavian Airlines, Singapore Airlines Swiss International Air Lines, TAP Air Portugal Turkish Airlines, Uzbekistan Airways	Satellite and G2A	Varies
Global Eagle Entertainment	Air France, Norwegian, Southwest Airlines, Turkish Airlines	Satellite	Varies
Thales Group	Singapore Airlines	G2A	Varies

2.1.4.7 Global Eagle Entertainment

There is a satellite-based service platform, Global Eagle Entertainment, which is used by many airlines around the world as an in-flight entertainment platform for connectivity and in-flight entertainment. As part of the company's e-entertainment services, the company also provides in-flight information services, e-commerce services and other related services. The service is used by a number of airlines, including Air France, Norwegian, Southwest Airlines and Turkish Airlines, to name a few.

2.1.4.8 Thales Group

Thales Group is also one of the leading providers of in-flight Internet services. FlytLIVE, Global Xpress, FlytLINK, GateSync, Oasis, inFlyt Global TV, InFlytRoam are Thales Group's specialized services for different regions and applications. Singapore Airlines is one of Thales Group's customers for providing in-flight connectivity and entertainment.

Thales, together with SkyFive and Nokia, will launch 4G LTE (ground to air) connectivity in the UK and claims that this solution will provide passengers with a fiber-like experience on board. This will enable high-definition streaming and advanced online gaming for users in the air.

To offer a nuanced understanding of the current landscape, Table 2.2 meticulously details a comparative analysis of prominent commercialized services within the aviation connectivity domain. This comprehensive table encapsulates crucial information, including the service providers, affiliated airlines, underlying technologies, and data rates. By synthesizing key features, performance metrics, and technological aspects, the table provides invaluable insights.

This comparison serves as a robust framework for situating our proposed Airborne Internet Access Mechanism within the contemporary state of the art, allowing for a more informed and contextualized exploration of our innovative approach.

TABLE 2.3: Comparison of existing satellite-based airborne Internet provision technique

Authors	Objectives	Approach	Limitations
Jahn et.al [44]	In-cabin entertainment	Satellite-Based	Slow and expensive, Only focus on entertainment
Khan [59]	Comapatively Internet provision with lower latency through multiple LEO satelites	LEO Satellites	Huge number of LEO satellites required. Less coverage
Reid et al[60]	Internet connectivity for navigation using commercial communication LEO constellation.	Satellite-Based	Mainly focus on terrestrial users
Volner and Boreš [48]	Claims to provide reliable and high-bandwidth Internet connectivity through distribution of data inside the aeroplane	Satellite-Based	High price and delay
Volner [46]	Method for uploading real-time flight-critical data to ground station through a satellite link to monitor flight status	Satellite-Based	High cost
Thanthry et al. [47]	Internet connectivity, and the data network, and associated security concerns for aeroplanes are covered.	Satellite-Based	High price and delay mainly focus on security
Vey et al [61]	Ad hoc network for flights flying over the sea	Satellite-Based	Only feasible for dense ad-hoc networks

TABLE 2.4: Comparison of existing hybrid and G2A- based airborne Internet provision technique

Authors	Objectives	Approach	Limitations
Jalali et al [62]	In-flight Internet through network of flying aircraft	Both satellite and G2A links	Costly when flying over ocean or remote areas
Sakhaee and Jamalipour [45]	Internet provision through cluster of aircraft. Concept of Big cache is presented	Both satellite and G2A links	Least feasible when using only satellite links.
Tadayon et al [63]	LTE based ground station-based method for delivering Internet in the air	G2A links	Only feasible for aircraft flying over land
Gupta and Aggarwal [64]	Airborne Internet through gateway aircraft connected to a ground station	G2A links	Only feasable for dense air traffic. Atleast one aircraft must be in the transmission range of ground station
Lynch et al [67]	Hybrid approach for transmitting online content to aircraft using both satellite and ground-to-air communication	Both satellite and G2A links	Aircraft flying over the ocean are not considered
Medina et al [51]	Airborne Internet through mesh networking	G2A links	Only feasable for dense air traffic. Atleast one aircraft must be in the transmission range of ground station

2.2 Gap Analysis

As discussed in the previous sections, there are several approaches to address the problem of in-flight Internet provision. However, the aforementioned approaches have focused only on basic Internet connectivity for less bandwidth-intensive applications (e.g., web browsing) and are unable to provide sufficient Internet speed to maintain QoS for modern web applications. Therefore, there is a need to improve and optimize Internet delivery techniques for aircraft flying over the seas. All existing solutions have their own set of problems, including the significant latency and costs associated with satellite-based systems, making them inadequate for modern Internet applications that require extremely low latency.

The G2A-based solutions, on the other hand, have their limitations, such as being suitable mainly for planes that fly over land rather than over water. They also lack scalability and reliability. Even the solutions specifically designed for airborne Internet for flights over oceans have their own issues. For example, [66] and [69] attempt to solve the problem of Internet in the air to some extent, through an ad hoc network. However, these solutions are not scalable, and during peak hours, network performance degrades significantly, making it difficult to provide reliable Internet for bandwidth-intensive applications. Most of the world's congested flight routes pass over inaccessible marine areas, and satellite links are often needed for Internet access for aircraft in such remote oceanic regions. However, these satellite links are costly and provide limited bandwidth. Equipping an aircraft with the tools required to provide Internet access through satellites is an expensive endeavor, with substantial upfront and monthly costs. Therefore, there is a pressing need for a low-cost, reliable, and high-speed Internet solution for aircraft in such remote regions.

2.3 Problem Statement

The problem addressed in this research is to provide efficient and reliable Internet access to aircraft flying over remote oceanic regions, especially in areas where congested flight routes pass over inaccessible marine areas. The challenges are significant, including the need for high-speed, low-latency connectivity to support modern web applications and ensure Quality of Service (QoS). Existing solutions, such as satellite-based systems, have issues related to cost, latency, and limited bandwidth. Ground-to-Air (G2A) solutions, while promising, have limitations in terms of coverage over water and scalability.

The specific problems to be addressed in this research are:

1. Implementing a novel and cost-effective airborne Internet provision mechanism for users and aircraft flying over oceanic regions.
2. Leveraging existing submarine optical fiber cables as a high-speed Internet backbone for wireless Internet access.
3. Developing the Airborne Ad-hoc Routing Algorithm (AARA) to ensure reliable and low-latency connectivity for aircraft flying away from the base stations in the sea to ensure scalability.

These problems directly link to the research objectives outlined in Section 1.9 and reflect our commitment to providing practical solutions to the challenges in providing efficient Internet access for aircraft over oceans.

2.4 Research Methodology

The methodology for conducting the proposed research is divided into two phases. In the first phase of research, a novel infrastructure for airborne Internet access via underwater optical fiber cables is presented. For this purpose, a detailed analytical framework is proposed, in which an injector and extractor are used to tap the main optical fiber cable under the sea. Beamforming technology is used for communication between aircraft and stationary ships stationed in the oceans. In the second phase, the proposed system will be compared with existing state-of-the-art solutions. Some enhancements were also made in earlier proposed work for reliable connectivity and increased scalability. To achieve this goal, a cost-effective, reliable transmission service solution for the Internet of Flying Things is proposed. A scalable version of the proposed solution is also presented that leverages air-to-air communication connectivity.

2.5 Current Advancements in the Field of Airborne Internet Access and Their Impact on the Proposed Research

After the publication of the research work proposed (in Sections 2.4 and 1.10 in the reputed journal of "IEEE Transactions on Aerospace and Electronic Systems", a number of explorations were reported that not only cited the authors' contributions but also made minor advancements. This section discusses these advancements as an addition to the literature survey. However, their results have been used for the performance comparisons (wherever necessary) in the subsequent chapters. Chen *et al.* devised an energy-efficient data access strategy based on reinforcement learning in civil airborne integrated space-air-ground networks [70]. The tradeoff between energy usage and delay, on the other hand, is not adequately addressed and can be further studied. In another research, Kong *et al.* analyze the outage performance of an aeronautical broadband satellite communication system using the amplify-and-forward protocol [71].

The phase error in the user link was considered. However, no new technique was proposed. Numani *et al.* investigated several routing algorithms for airborne Internet using underwater fiber optic cables [72]. Another study that describes the characterization of existing in-flight Internet systems operated by various airlines is presented in [73]. The authors used over 45 hours of measurements from 16 flights operated by six different airlines. However, no technology is proposed in this study. Instead, latency and throughput in the deployed systems are used to determine QoS. Instead, latency and throughput in deployed systems are used to determine QoS. Savanoor *et al.* in [74] discussed the use of aerial Internet to deliver broadband Internet connectivity to disaster-stricken areas. However, this is not an airborne Internet access solution for aerial users but rather a system for providing Internet to terrestrial users via planes and drones. Vondra *et al.* compared the performance of 4G and 5G-based A2G communications and LEO satellites with a channel bandwidth of 20 MHz using beamforming. However, this solution is limited to aircraft flying over land [75].

To reduce network traffic latency and achieve load balancing across ground base stations, Wan *et al.* presented a software-defined A2G architecture and in-flight Internet access redirecting mechanism [76].

The frequency of rerouting is compared to the delay and traffic load to evaluate this study. This approach, however, has significant flaws, including a tradeoff between optimal flow arrangement and minimizing reroute frequency. The high time complexity and frequent diversion may make it impracticable in most circumstances.

Chapter 3

Proposed Airborne Internet Access Through Submarine Optical Fiber Cables

In this chapter, a practical exploration of the proposed system model and the detailed design of an airborne Internet access network is undertaken. Chapter 3 serves as a direct continuation of the comprehensive study initiated in Chapter 1, where the motivation and overarching objectives of the research were introduced. The upcoming section, labeled 3.1, provides a comprehensive overview of key aspects of the system model, laying the foundation for in-depth discussions in later chapters. This section serves as a critical exploration of the theoretical underpinnings that form the basis of the innovative approach to delivering Internet access to aircraft over the North Atlantic Ocean. Section 3.2 serves as a starting point, unveiling the foundational principles that underpin the vision for delivering Internet access to aircraft traversing the North Atlantic Ocean.

The journey begins with an in-depth exploration of the proposed system model in Section 3.3, where the theoretical groundwork for the innovative approach is laid. Subsequently, in Section 3.4, the transition from theory to practical implementation is made, delving into the intricate details of the proposed airborne Internet access network design. This network leverages the extensive submarine optical cable infrastructure to offer high-speed and reliable Internet to aircraft, cargo ships, and small vessels, eliminating the need for costly satellite links and significantly enhancing Internet capacity.

The narrative in Chapter 3 is intertwined with the foundational principles and motivation elucidated in Chapter 1.

This chapter represents the convergence of theoretical research with practical implementation, offering a tangible blueprint for the realization of our objectives. As the exploration continues, the transformative potential of the innovative system model and airborne Internet access network is unveiled.

3.1 System Model Overview

In this section, a comprehensive overview of various critical aspects of the system model is provided, laying the foundation for subsequent detailed discussions in later chapters.

3.1.1 Height and Elevation Angle of Arrival

In our aerial communication system, understanding the height (h) and elevation angle of arrival (θ_{arr}) of aerial nodes is crucial. The height is defined as the vertical distance of an aerial station (AS) above the ground level, influencing the line-of-sight and signal coverage. The elevation angle of arrival represents the angle at which signals from the AS arrive at the base stations (BSs), impacting signal propagation characteristics significantly.

3.1.2 Propagation Path-Loss Model

The system relies on a sophisticated propagation path-loss model to characterize signal attenuation over distance. The power received at a certain distance (d_i) from the i^{th} BS is expressed using the path-loss exponent (n) and a reference distance (d_o). This model, often represented in a logarithmic scale, is a fundamental component in predicting signal strength at different distances.

$$p_{r,i}(d_i) = K_1 - K_{2,i}\ \log_{10}(d_i) \tag{3.1}$$

Here, K_1 and $K_{2,i}$ are constants dependent on the reference distance, measured power, and path-loss exponent.

3.1.3 Signal Strength and Power Control

Continuous monitoring of signal strength from BSs is a critical aspect of our system. Power control mechanisms are implemented to manage signal strength dynamically, ensuring optimal communication quality.

The received power profile matrix, $\mathbf{P}_r$, contains vectors of received power from serving and candidate BSs, forming a crucial component for the handover mechanism.

3.1.4 Handover Mechanism

Our system implements a robust analytical handover model based on propagation path loss. The handover decision is triggered by a sophisticated algorithm that takes into account various factors, including the power from the serving BS decreasing below a predefined threshold.

This ensures a seamless transition between cells, maintaining uninterrupted communication.

3.1.5 Other Relevant Parameters

Numerous additional parameters contribute to the comprehensive system model. These include the impact of the propagation environment (K_2) on handover span, AS velocity (v), and residual power ratios.

Each of these parameters plays a unique role in shaping the dynamics of our airborne communication system.

This consolidated and detailed overview sets the stage for an in-depth exploration of each aspect in subsequent chapters.

3.2 Introduction to Airborne Internet Access Through Submarine Optical Fiber Cables

In this section, an introductory overview of the innovative concept of delivering Internet access to aircraft flying over the North Atlantic Ocean through the strategic use of submarine optical fiber cables is presented. While Chapter 1 sets the stage by introducing the motivation and overarching objectives of our research, this chapter serves as a practical exploration of our proposed system model and the detailed design of an airborne Internet access network.

The transition from the theoretical framework to the practical realization of the vision is undertaken in this chapter, presenting a comprehensive blueprint for providing high-speed, reliable Internet connectivity to aircraft. The core of our approach lies in the seamless integration of stationary ships stationed along submarine optical cables, each equipped with the technology necessary to facilitate this groundbreaking Internet access. Our objective is to eliminate the need for costly satellite links, thereby significantly enhancing Internet capacity and transforming the digital landscape for air travelers.

The pivotal role of Chapter 1 in setting the stage for the practical implementation presented here is acknowledged as we delve into the intricate details and operational aspects of our proposed system.

This chapter represents the convergence of theoretical research with practical implementation, offering a tangible path toward the realization of our objectives. The reader is invited to accompany us on this journey, uncovering the transformative potential of our innovative system model and the airborne Internet access network.

The innovative system model, detailed in the following sections, aims to provide Internet connectivity to aircraft flying over the North Atlantic Ocean through wireless links from stationary ships stationed along the submarine optical cables. These ships, seamlessly integrated into the existing infrastructure, are equipped with the necessary technology to make this visionary Internet access a reality. Subsequently, we'll delve into the intricate details of the proposed airborne Internet access network design, leveraging the extensive submarine optical cable infrastructure to offer high-speed and reliable Internet to aircraft, cargo ships, and small vessels.

3.3 Proposed System Model

This section presents the proposed approach to provide Internet to aircraft flying across the North Atlantic Ocean through wireless links from the stationary ships stationed along the submarine optical cables. These ships will be connected to the submarine optical cables and will be equipped with the terminal, power feeding, and other necessary equipment as in submarine cable landing stations. The proposed airborne Internet service avoids expensive satellite links and in turn, improves the Internet user capacity tremendously.

It is generally known that the majority of undersea optical cables connecting the continents of the world are laid on the ocean floor and transport high-speed traffic across the oceans. On the globe map, the majority of busy air traffic routes and underwater optical fiber cables routes follow the same course. Therefore, there are several potentials to harness existing optical fiber cable infrastructure to offer aircraft, cargo ships, and small vessels with high-speed and reliable Internet. Using already-installed submarine cables with a high capacity, Internet service providers can provide Internet to planes flying over the Atlantic at prices comparable to those for residential users in the United Kingdom and the United States. An overview of the air traffic routes and submarine optical fiber installation in the NAC is shown in Figure. 3.1 and 3.2 respectively.

The operation, maintenance, and servicing of the submarine cables is performed using service ships. Similar ships can be stationed in the ocean and connected to the Internet backbone via the submarine optical fiber cables. Other than these ships, infrastructure installed on remote oceanic islands can also be served as Base stations (BSs). These ships can then be dedicated to serve as BSs for not only providing

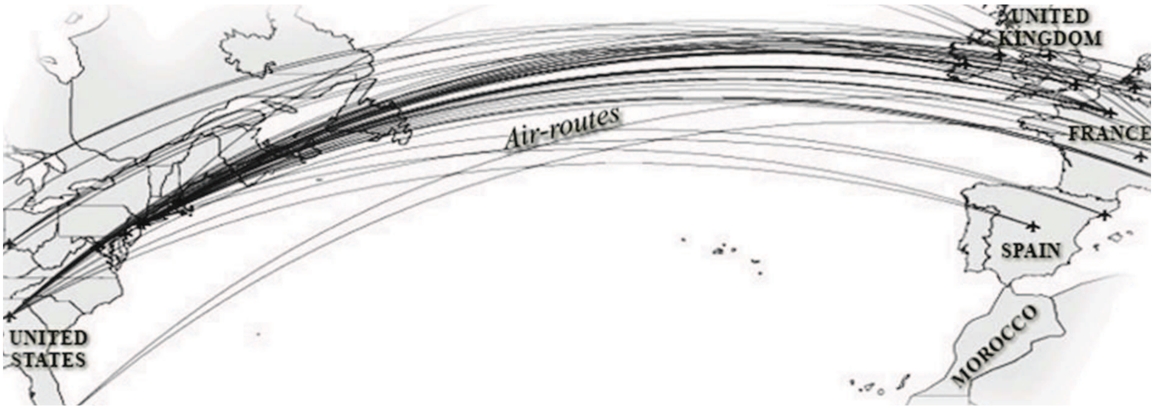


Figure 3.1: The North Atlantic Air Routes [77]

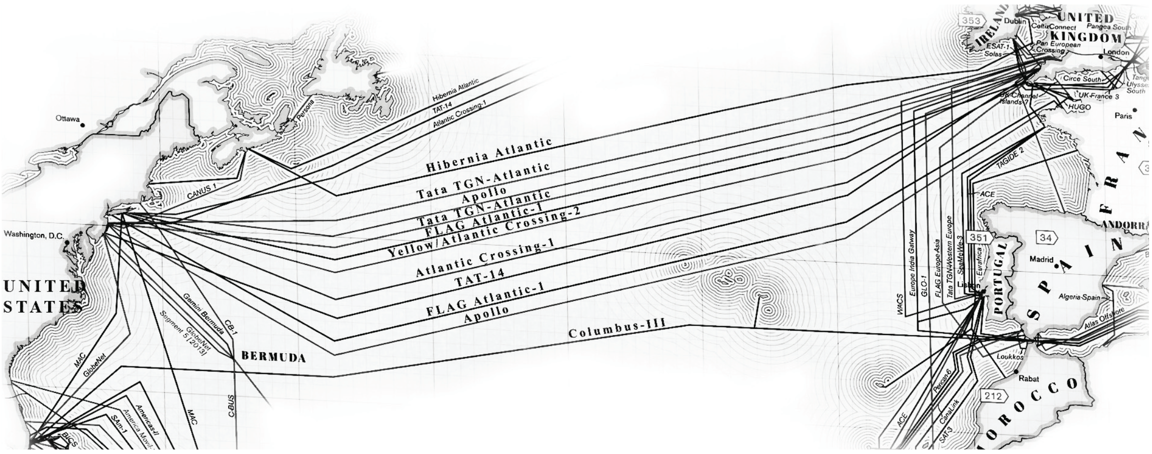


Figure 3.2: North Atlantic submarine optical fiber cable routes [78].

Internet to other cargo ships (denoted as Oceanic stations (OS)) and aircraft (denoted as Air Stations (ASs)), but also providing navigation services. These dedicated ships can be placed at uniform distances from one another as shown in Figure. 3.3, along any of the high capacity submarine optical fiber cables.

In terrestrial and marine propagation conditions, communication channels between BS and AS and between BS and OS are often unobstructed, clear Line of Sight (LoS) channels. In such circumstances, free space path loss is a significant element in the attenuation of the communication link. Since there is no dense scattering environment beyond the line of sight, only a few weakly dispersed signals reach the receiver, resulting in a severe degradation of communications. The range of line-of-sight (LoS) communication is restricted due to the spherical geometry of the earth's surface, as shown in Figure. 3.4. So, the radius of the Earth (r_e) and the height of the flying aircraft (h_a) can be used to figure out the maximum LoS communication range. All aircraft are assumed to fly at the same altitude, $h_a = 10.688$km (i.e.,

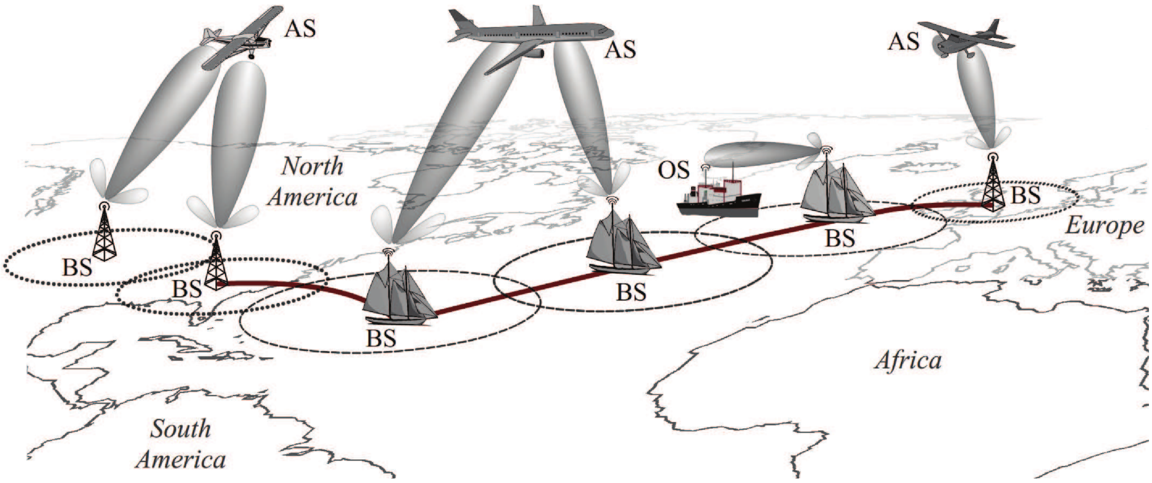


Figure 3.3: Airborne Internet access through stationary ships stationed along the submarine optical fiber cables.

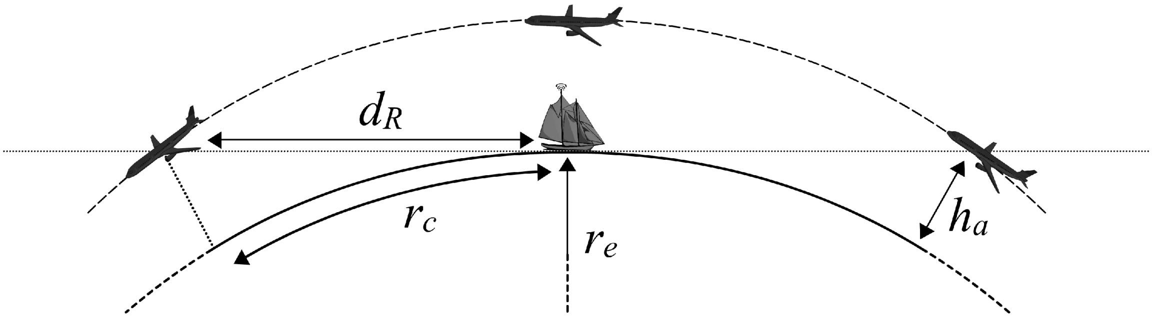


Figure 3.4: LoS range of A2G and G2A communication Link.

35000ft) [79].

Therefore, the maximum possible radius $r_{c,\max}$ of an airframe can be determined by the maximum LoS range between AS and BS, which can be calculated as follows,

$$r_{c,\max} = \arccos\left(\frac{r_e}{r_e + h_a}\right)\frac{\pi r_e}{180^0} \tag{3.2}$$

The maximum possible radius of a cell, $r_{c,\max}$, can then be calculated as 368.98km, by setting $r_e = 6378.137$km and $h_a = 10.688$km in (3.2). The oceanic distance from Europe to USA is approximately 5500km.

As discussed earlier, each BS is supposed to provide Internet coverage to a cellular region of radius 368.98km. If the overlapping region's width of two adjacent cells is taken as 10km, for covering the entire North Atlantic region between Europe and the United States, eight cells are required based on the maximum radius of a single cell,

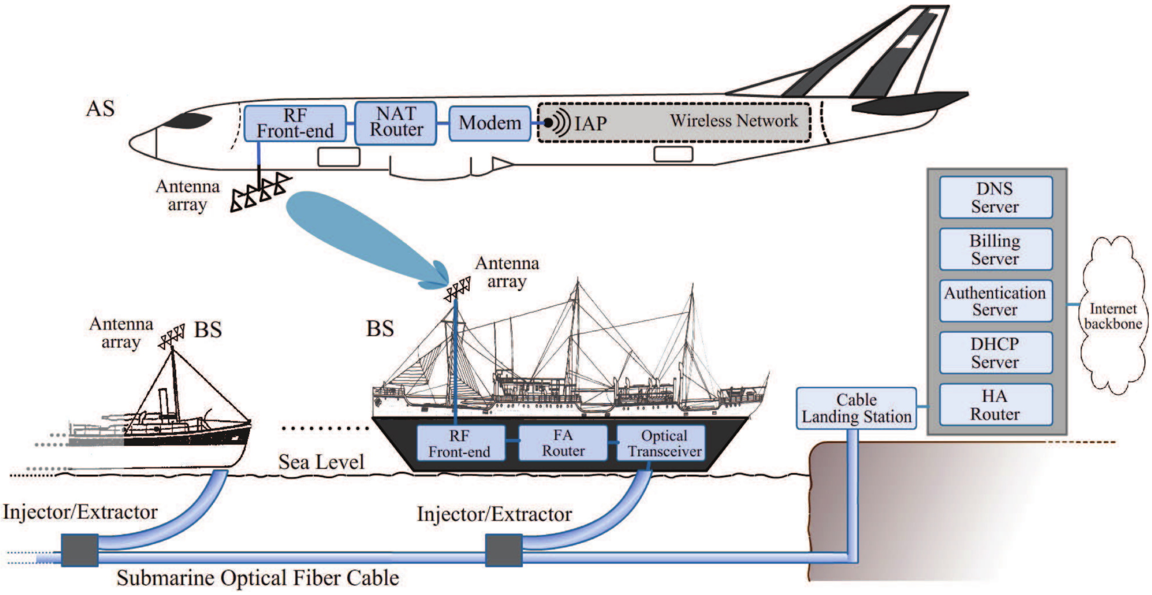


Figure 3.5: Detailed design of communication network for airborne Internet through submarine optical fiber cables.

and assuming that the ships are evenly spaced. The transmit power required to cover a cell with a radius of $368.98[km]$ can be calculated as $57.8[dBm]$, assuming isotropic transmit and receive antennas, a path loss exponent of $n = 2$, and a minimum receive power of $-100[dBm]$. The power requirement can be significantly reduced if smart antennas with high directional gain are used. To calculate the azimuth and elevation direction of the incoming signal, it is assumed that BS and AS have planar smart antennas.

For A2G and G2A communication links, these antennas steer narrow beams in the desired direction with an optimal signal-to-noise ratio. This can be achieved by adaptive tuning of the array's antenna elements. In addition, tidal power plants and wind turbines can be used on BS vessels to generate the power needed for communications equipment.

In the following lines, we explore the maximum capacity for simultaneous aircraft connection to a single ship/OS in our research. This is an important aspect of our system, as it determines how many aircraft can benefit from the high-speed, low-latency, and reliable internet access provided by the submarine optical fiber cables. We elaborate on the factors influencing this capacity and its implications for effective ship-aircraft connectivity. The capacity of our system depends on several factors, such as the distance between the ship and the aircraft, the communication protocol, the interference level, and the quality of service requirements. In general, the more antennas the ship has, the more aircraft it can serve simultaneously, as it can use beamforming techniques to steer multiple beams towards different directions. However, this also increases the complexity and the power consumption of the system and may require more feedback from the aircraft.

One way to estimate the maximum capacity is to use the formula that we discussed in the previous message:

$$N_{max} = \frac{N_{RF}}{N_s}$$

where N_{max} is the maximum number of aircraft, N_{RF} is the number of radio frequency (RF) chains, and N_s is the number of data streams per aircraft. This formula assumes that each RF chain can serve one aircraft with one data stream and that each aircraft can be allocated multiple RF chains. For example, if we assume that the ship has 256 antennas and 64 RF chains and that each aircraft requires 4 data streams, then the maximum number of aircraft that can connect to the ship simultaneously would be:

$$N_{max} = \frac{64}{4} = 16$$

However, it's worth acknowledging that this rough approximation might not capture the intricate dynamics influenced by factors like channel conditions, communication algorithms, interference, and quality of service requirements. To attain a more nuanced understanding, a detailed simulation or measurement of the system under diverse scenarios would be advisable. This approach could offer a more comprehensive and reliable assessment, taking into account the complexities inherent in real-world operational conditions. The implications of this capacity for effective ship-aircraft connectivity are significant, as it can enable airborne internet access through submarine optical fiber cables, which is the main focus of our research. By connecting multiple aircraft to a ship that is linked to a submarine cable, the system can provide high-speed, low-latency, and reliable internet access to the aircraft, which can improve the passenger experience, flight safety, and operational efficiency. Moreover, the system can also support other applications, such as remote sensing, surveillance, and navigation, that require high data rates and low delays.

3.4 Proposed Airborne Internet Access Network Design

As discussed in the previous section, each BS ship transmits a beacon, or pilot signal. Every aircraft passing through the coverage region searches for the pilot signals from the BSs. It then connects to a certain BS with the strongest pilot signals.

The sea BSs, vital components of the airborne Internet access network, are interconnected with the submarine cable through a crucial interface known as the "Injector/Extractor," as illustrated in Figure 3.5. It is noteworthy that the establishment of these connections involves the utilization of specialized maintenance and installation tools on cable ships [80]. This process ensures the seamless integration of the "Injector/Extractor" into the existing optical fiber system. The "Injector/Extractor" serves a pivotal role in maintaining the overall capacity of the optical fiber system without causing interruptions to the ongoing traffic [81]. A distinctive feature of this component is its capability to handle multiple single-mode optical fiber signals. This enables the insertion and extraction of signals from the primary optical fiber cable, presenting a practical and efficient alternative to the conventional approach.

Traditionally, the alternative method involves the splitting of the cable, followed by splicing it to the couplers of Dense Wavelength Division Multiplexing (DWDM) equipment [82]. However, the introduced "Injector/Extractor" mechanism streamlines this process, offering a more versatile and effective solution for incorporating multiple signals into and out of the main optical fiber cable.

This detailed discussion aims to provide a comprehensive insight into the practical aspects of the "Injector/Extractor," addressing its feasibility, installation methods, and its role in maintaining the integrity of the optical fiber system.

The decision and function of the handover process are assumed to be controlled by AS. When the power of the pilot signal received at AS from the neighboring BS (i.e., the target) increases from that of the serving BS by a certain threshold level, the handover is performed. Mobile IP enables the aircraft's mobility between two BSs without change in its IP address [83]. The Home Agent (HA) router is placed at the landing station of the submarine optical cable, while the Foreign Agent (FA) router is placed at the BS. The landing station also contains other important servers like Domain Name Server (DNS) (for conversion of URL to IP addresses), Authentication Server, Billing Server, Dynamic Host Configuration Protocol (DHCP) server, etc. The Authentication Server facilitates the authentication process of giving access to a new AS from a certain BS. Afterwards, the HA router assigns the IP address to the AS using DHCP implemented in the DHCP Server. During the handover process, the AS is assigned a care-of address by the FA server at the target BS after authentication. This care-of address is also notified to the HA router, so that, the HA router tunnels the data to the desired FA router. It is assumed that the transmission format of the optical fiber signal conforms to the Synchronous Digital Hierarchy (SDH) standard. All the routers use SDH-compliant ports. The optical signal received by the BS from the cable is then converted to electrical form by using Optical To Electrical (OTE) converters. The output of OTE is connected to the FA router which is further connected to the AS router through an uplink radio channel using smart antennas. The WiFi modems provide Internet coverage inside the aircraft. In the A2G link, the data from the AS is eventually received by the Electrical To Optical (ETO) converter in the optical transceiver and then injected into the optical fiber cable. Any physical-layer access technology, like Code Division Multiple Access (CDMA), Orthogonal Frequency Division Multiple Access (OFMDA), etc, can be used as the Radio Access Technology (RAT) for the proposed system. The base station controllers present the BSs and allocate the time/frequency resources, structured as channels, to the connected ASs. Since, the existing 4G radio access technologies, like WiMax and LTE, are OFDMA-based, OFDMA can be seen as the appropriate candidate for being RAT in the proposed system. Such technologies can be used for the proposed system with slight modifications. The existing RAT has certain limitations, e.g., the maximum supported cell range is 100km. The proposed cell radius, in order to reduce the total number of required BSs, is about 369km. Cell radius, in the case of advanced versions of Wimax, is determined by the ranging procedure. The ranging procedure is meant to achieve dynamic time alignment in uplink transmissions from MSs, which are usually at different distances from the BSs. These transmissions are not only synchronized with one another but also arrive in their respective receive slots. The existing ranging procedure for the RAT is required to be modified in order to take into account the larger cell radii of A2G and G2A communication links. A smart scheduling algorithm is also of paramount importance to allocate the required number of slots to an AS to satisfy the Quality of Service (QoS) requirements. The existing signaling mechanisms can be used for signaling between the sea BSs and the Landing station. Since, modern wireless technologies that may be used as RAT for the proposed systems are mainly based on packet routing, end-to-end delay and other QoS guarantees become essentially important. End-to-end delay guarantees can be provided by making use of appropriate QoS mechanisms available in the literature. A well-established multilayer approach can be utilized for the provision of such guarantees. At the physical layer, the proposal involves equipping Aerial Stations (ASs) and Base Stations (BSs) with highly directional antennas for backbone beamforming to ensure optimal coverage.

Broadband G2A and BS-to-Landing Station links require a medium access control (MAC) protocol capable of handling high traffic loads in the network and providing QoS guarantees to the AS and BS. At the network layer, QoS routing protocols are also of imminent need. International consortiums involving various investors from financially strong countries were formed to lay and administer submarine optical fibers for connecting the telecommunication services of different countries and continents, like, SEA-ME-WE 3 and TAT-14, etc. The existing consortium does not have such a mandate to authorize Internet providers for such use of existing optical fibers as proposed in this paper. Now with the growing importance of high-speed ubiquitous Internet provision, it is necessary to amend the mandate of the existing consortium to permit such use of optical submarine cables.

3.4.1 Detailed Explanation of the Network Architecture Inside the Aircraft

The network inside the aircraft is designed to facilitate airborne internet access through submarine optical fiber cables. The architecture comprises several components, each playing a crucial role in the network operation. The first component is the Radio Frequency (RF) Front-end. The RF Front-end is responsible for receiving signals from the base station via the antenna array. It performs functions such as signal amplification, frequency conversion, and filtering. These functions are essential

for maintaining the quality and integrity of the signals received.
Next, the signals are passed to the Network Address Translation (NAT) Router. The NAT Router modifies network address information in packet headers while in transit across a traffic routing device. This process, known as IP masquerading, effectively hides an entire IP address space, usually consisting of private IP addresses, behind a single IP address in another, usually public address space. This is particularly useful in conserving the limited number of public IP addresses available, and also adds a layer of security by hiding the internal IP addresses from the external network.

Incorporating Mobile IP into this architecture is pivotal for ensuring continuous internet connectivity, especially during flight. Mobile IP is a standard communication protocol developed by IETF, designed to allow mobile device users to move from one network to another while maintaining their original IP address. This ensures that ongoing sessions are not interrupted by such transitions.

Within the aircraft's network architecture, Mobile IP would work as follows:

- **Home Agent (HA)**: The HA is located in the home network. It keeps track of the mobile device's current location identified by its Care-of Address (CoA). It intercepts packets destined for the mobile device and tunnels them to its CoA.
- **Foreign Agent (FA)**: When an onboard device moves into a new network or changes its point of attachment within the airborne network, the FA assists in delivering tunneled packets from the HA to the mobile device.
- **Care-of Address (CoA)**: This temporary IP address enables the routing of packets when a mobile device is connected to a foreign network or different subnet within the aircraft.

The integration of Mobile IP ensures that passengers' devices automatically adjust without requiring changes in their IP settings or interruptions in ongoing data transmissions.

It enhances user experience by providing seamless roaming capabilities across various onboard subnets and even between ground-based networks and airborne networks. The NAT Router is connected to a Modem, which facilitates data transmission by modulating and demodulating signals for transmitting or receiving data, respectively. The modem converts the digital data from the computer into a format suitable for transmission over the network. Following the Modem is the Internet Access Portal (IAP). The IAP serves as an interface for users to connect to the internet. It acts as a gateway and manages traffic between the onboard wireless network and the external internet source. The IAP also handles user authentication, ensuring that only authorized users can access the internet.

Finally, the Wireless Network allows passengers and crew to connect their devices wirelessly. The network is likely secured and may offer different tiers of service or restrictions based on user type or service purchased. This provides flexibility and convenience to the users, enhancing their in-flight experience.

The Transmission Control Protocol/Internet Protocol (TCP/IP) suite will be used in this network architecture. The TCP/IP suite is a robust and adaptable set of protocols that has been the backbone of Internet communications for decades. Its proven reliability, efficiency, and scalability make it an ideal choice for airborne internet access. The TCP/IP suite's layered architecture allows for the separation of concerns, making it easier to manage and troubleshoot. Furthermore, it supports a wide range of applications and services, ensuring compatibility with existing systems and future-proofing against technological advancements.

3.4.2 Detailed Explanation of the Land-side Network Architecture

The land-side network architecture is designed to support the airborne internet access system. It comprises several servers and routers, each playing a crucial role in the network operation.

The first component is the Domain Name System (DNS) Server. The DNS Server is responsible for translating domain names into IP addresses. This allows devices to access websites using human-readable names rather than numerical IP addresses. Next, the Dynamic Host Configuration Protocol (DHCP) Server dynamically assigns

IP addresses to devices on the network. This simplifies network administration by providing automatic IP address configuration to devices, eliminating the need for manual assignment.

The Billing Server is responsible for managing the billing information for users. It tracks the usage of network resources by each user and generates billing data accordingly. This ensures that users are billed accurately for the services they use. Whereas, the Authentication Server verifies the credentials of users before granting them access to the network. This adds an additional layer of security, preventing unauthorized access. Finally, the Home Agent (HA) Router manages the routing of data packets in the network. It maintains a mapping of each mobile node's home address with its care-of address and uses this information to forward data packets to the correct destination. The land-side network architecture ensures reliable, high-speed internet access for airborne users, leveraging the robustness of submarine optical fiber cables for internet connectivity. The use of a DNS Server, DHCP Server, Billing Server, Authentication Server, and HA Router enhances the security, manageability, and efficiency of the network.

Chapter 4

Proposed Seamless Connectivity Provision and Handover Performance Analysis

In the realm of high-mobility scenarios, the intricacies of handover processes become paramount. This chapter undertakes a comprehensive analysis, delving into the nuanced factors that influence handover duration, including the velocity and movement direction of aircraft, along with the characteristics of the propagation environment. The duration of handovers plays a pivotal role in the strategic planning of radio cells, particularly concerning the overlapping regions between adjacent cells. Broad overlap zones are strategically established to meet the Quality of Service (QoS) requirements, effectively managing traffic changeover delays.

The study incorporates both cell geometric models and propagation loss models to investigate handover dynamics. Section 4.1 intricately explores the mechanisms of seamless connectivity, laying the groundwork for subsequent discussions. Section 4.2 presents an analytical handover model based on cell geometry, while Section 4.3 introduces a parallel model based on path loss considerations. The performance of these handover models is meticulously examined in Section 4.4.

Beyond technical aspects, legal considerations for deploying the proposed solution are addressed in Section 4.5, providing a comprehensive perspective on the regulatory landscape. The chapter culminates with Section 4.6, offering a succinct summary and key findings that encapsulate the multifaceted exploration of handover dynamics in high-mobility scenarios.

4.1 Seamless Connectivity Provision Mechanisms

In this section, the core of the proposed method for achieving seamless connectivity in airborne networks is explored. While ground-based networks employ various handover methods, airborne networks pose unique challenges due to high mobility and dynamic environments.

The focus lies in seamlessly connecting aircraft networks, which rely on satellite and ground base stations, and the handover procedures are categorized into two primary types: 1) Handover in satellite communication and 2) Handover in ground-to-air communication.

4.1.1 Background on Satellite Handovers

While satellite-based handovers are a common approach for airborne networks, it's essential to provide an understanding of these methods for context. In satellite communications, handovers are typically required when an aircraft transitions from one satellite's coverage area to another. These handovers involve control, resource changes, and quality of service (QoS) adjustments to maintain seamless connectivity.

In the context of satellite communications, various handover mechanisms are employed, including spot beam handovers and satellite handovers.

4.1.1.1 Spot Beam Handover

One prevalent handover mechanism is the ”spot beam handover.” In this approach, a satellite's coverage area, known as its footprint on Earth's surface, is subdivided into smaller cells or spot beams. This division optimizes frequency utilization and minimizes interference by using identical frequencies in non-adjacent spot beams. Spot beam handovers ensure uninterrupted communication, as the ongoing link between the user and the current spot beam is handed over to the next spot beam when needed. This process occurs within the same satellite, eliminating the involvement of other satellites. While spot beam handovers are common in low Earth orbit (LEO) satellite systems, it's important to note that this approach may not be directly relevant to our ground-based handover solution, which focuses on ground-to-air (G2A) communication.

4.1.1.2 Satellite Handover

Satellite handovers, another category of handover mechanisms, are significant in scenarios where an aircraft's speed differs substantially from that of a satellite, potentially causing connectivity interruptions. These handovers involve transferring the connection from one satellite to another when the serving satellite can no longer provide service to a user. These handovers are relevant in low Earth orbit satellite-based diversity systems. Satellite handovers offer unique challenges compared to spot beam handovers, as they involve selecting the best satellite based on factors like communication quality.

However, for our research, which focuses on G2A communication, the emphasis lies on optimizing ground-based handovers to accommodate the high-speed and predictable trajectories of aircraft.

4.1.2 Ground-to-Air (G2A) Communication Handovers

In the realm of ground-to-air (G2A) communication, ensuring uninterrupted Internet connectivity for aircraft is a complex endeavor. Unlike traditional terrestrial mobile networks, G2A systems face unique challenges due to the high-speed and constant trajectory of aircraft.

One example of a G2A communication solution is GoGo, which points cellular networks skyward, effectively extending coverage to aircraft. G2A towers, such as those used by GoGo, are strategically positioned at calculated distances to guarantee seamless connectivity for uninterrupted service delivery. This positioning, combined with advanced handover mechanisms, ensures that aircraft can maintain consistent Internet access as they traverse the sky. This subsection offers an overview of G2A communication and emphasizes the significance of seamless handovers. The need for more detailed technical insights is acknowledged. For a deeper understanding, exploration of upcoming sections is encouraged, which will delve into analytical models and practical solutions.

Section 4.2 delves into geometric models for understanding handovers, while 4.3 explores propagation models.

These upcoming sections will provide comprehensive insights into the technical techniques and solutions developed to ensure uninterrupted Internet access for aircraft traveling at high speeds. For now, this section sets the stage for a more detailed exploration.

4.2 Analytical Handover Model Based on Cell-Geometry

In this section, an analytical handover model is presented based on the cell geometry of the proposed airborne internet access network design introduced in Chapter 3.

The Aerial Station (AS) is considered to be moving with velocity v and its distance from the Base Stations (BSs) is depicted in Figure. 4.1.

The distance of the AS from the BS_1 and BS_2 projected on the horizontal ground plane is represented by d_1 and d_2 respectively. These horizontal distances can be found, e.g., the distance of AS from BS_1, as

$$d_1 = \sqrt{d_{\mathrm{BS}_1}^2 - h_{\mathrm{AS}}^2} \tag{4.1}$$

Radius of each cell is shown by r_c. The radius of a cell depends upon the height of the AS, h_{AS}, as shown in the Figure. 4.2, which can be expressed as.

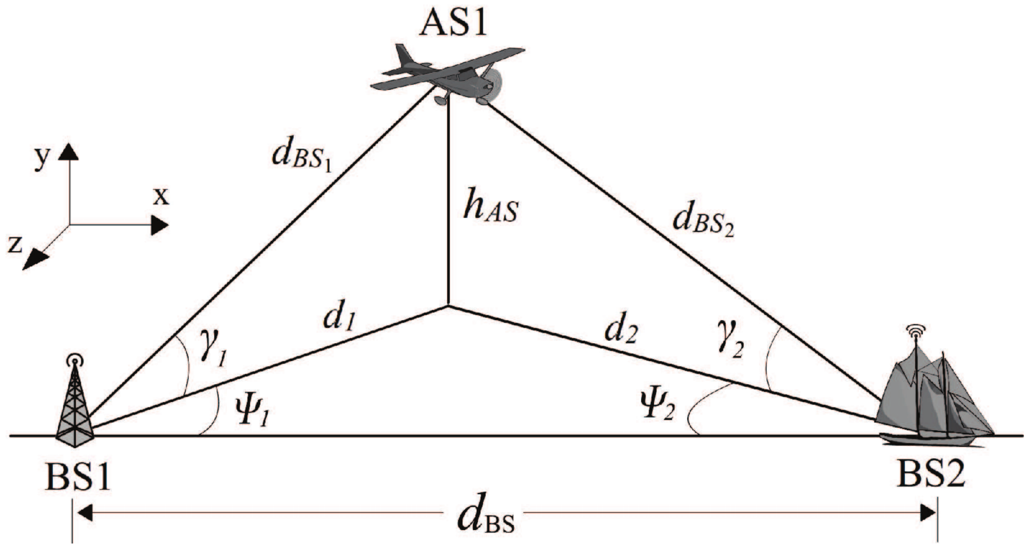


FIGURE 4.1: The land mobile radio cellular network with a Air Station (AS) at boundary of a cell.

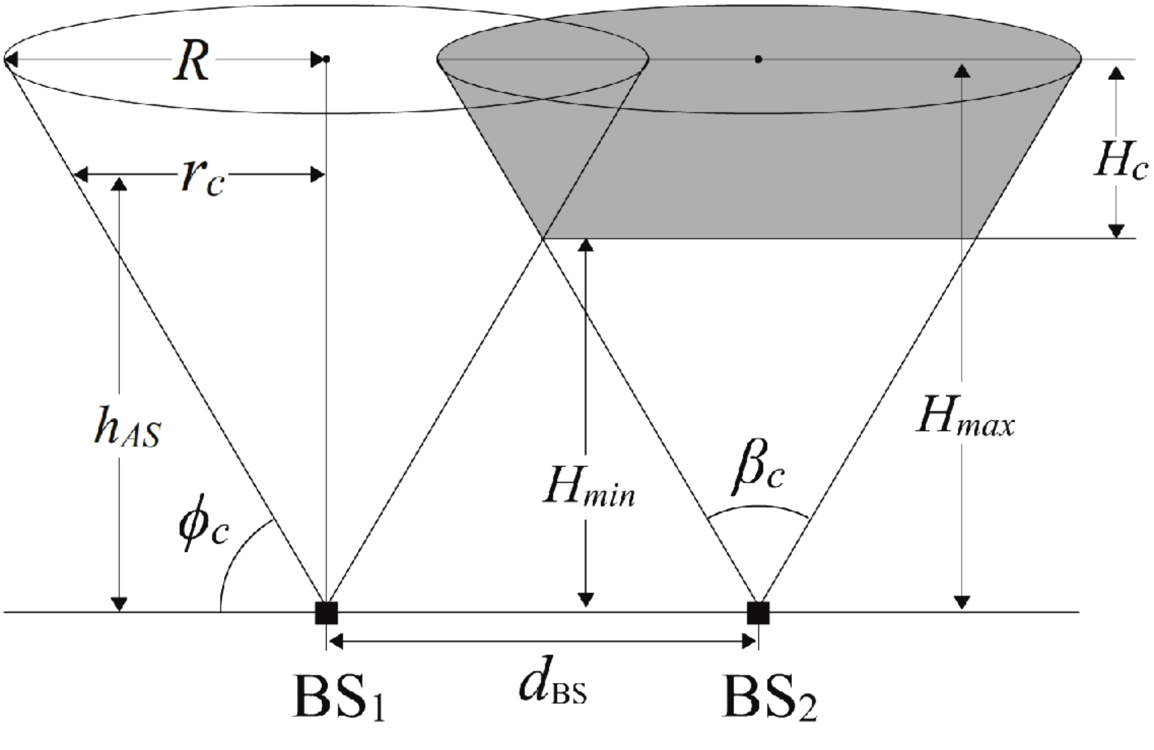


FIGURE 4.2: Side view of the land mobile Radio cellular Network.

$$r_c = h_{\text{AS}} \tan\left(\frac{\beta_c}{2}\right) \tag{4.2}$$

where, β_c is the maximum spread of the beamwidth of the antenna at a BS. Given a β_c value, $H_{min} = \frac{d_{BS}}{2}\tan(\frac{\pi-\beta_c}{2})$, determines the minimum flying altitude of an AS to avoid any blind zones in the signal coverage (see Figure. 4.2).

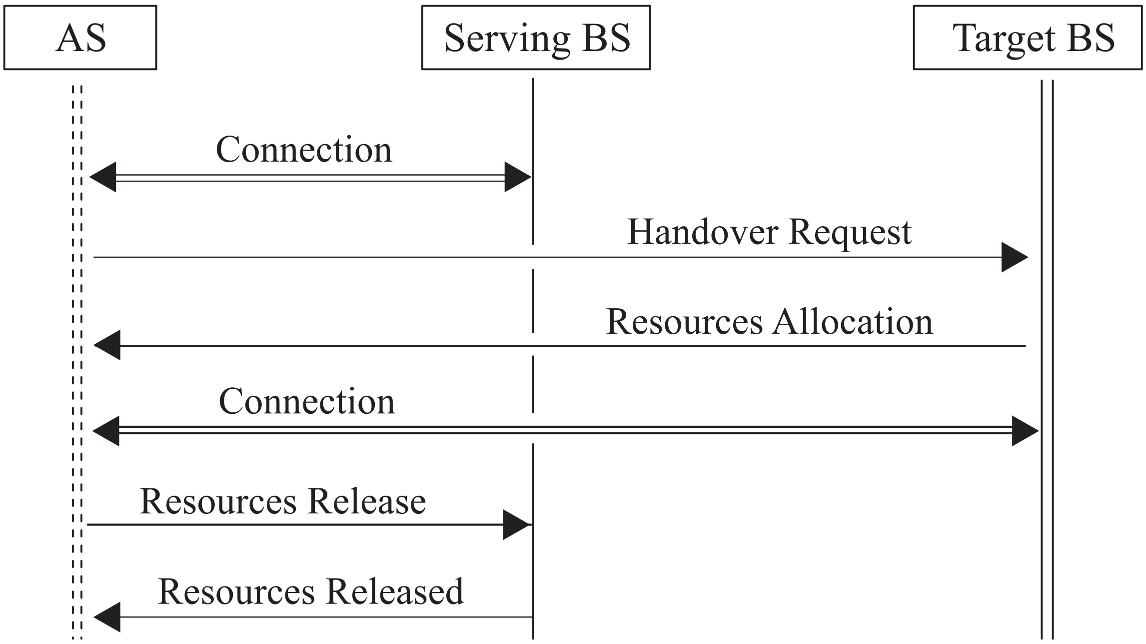


FIGURE 4.3: The land mobile radio cellular network with a AS at boundary of a cell.

The scenario of handover, when an AS moves from a serving cell to an adjacent cell is depicted in Figure. 4.3.

The top view of the land mobile radio cellular network with serving and target BSs is shown in Figure. 4.4. The direction of AS's motion with respect to the line joining BS_1 to BS_2 is θ_{AS}. The angle-of-arrival (AoA) of LoS component from the AS received at BS_1 and BS_2 are shown by Ψ_1 and Ψ_2, respectively. d_{OR} is the maximum horizontal width of the overlapped region between two adjacent cells. The distance d_τ is the horizontal distance which AS has to travel between the points of initiating and completing the handover.

The starting position of the AS is assumed to be known at the serving BS (i.e. BS_1) in form of the angle Ψ_1 and distance d_1 as shown in Figure. 4.4. The distance of AS from the BS of adjacent cell (i.e., BS_2) is shown by d_2, which can be found as

$$d_2 = \sqrt{d_{\mathrm{BS}}^2 + d_1^2 - 2d_{\mathrm{BS}}d_1\cos(\Psi_1)} \tag{4.3}$$

Also, the azimuthal AoA of LoS component observed at the BS_2 can be found as,

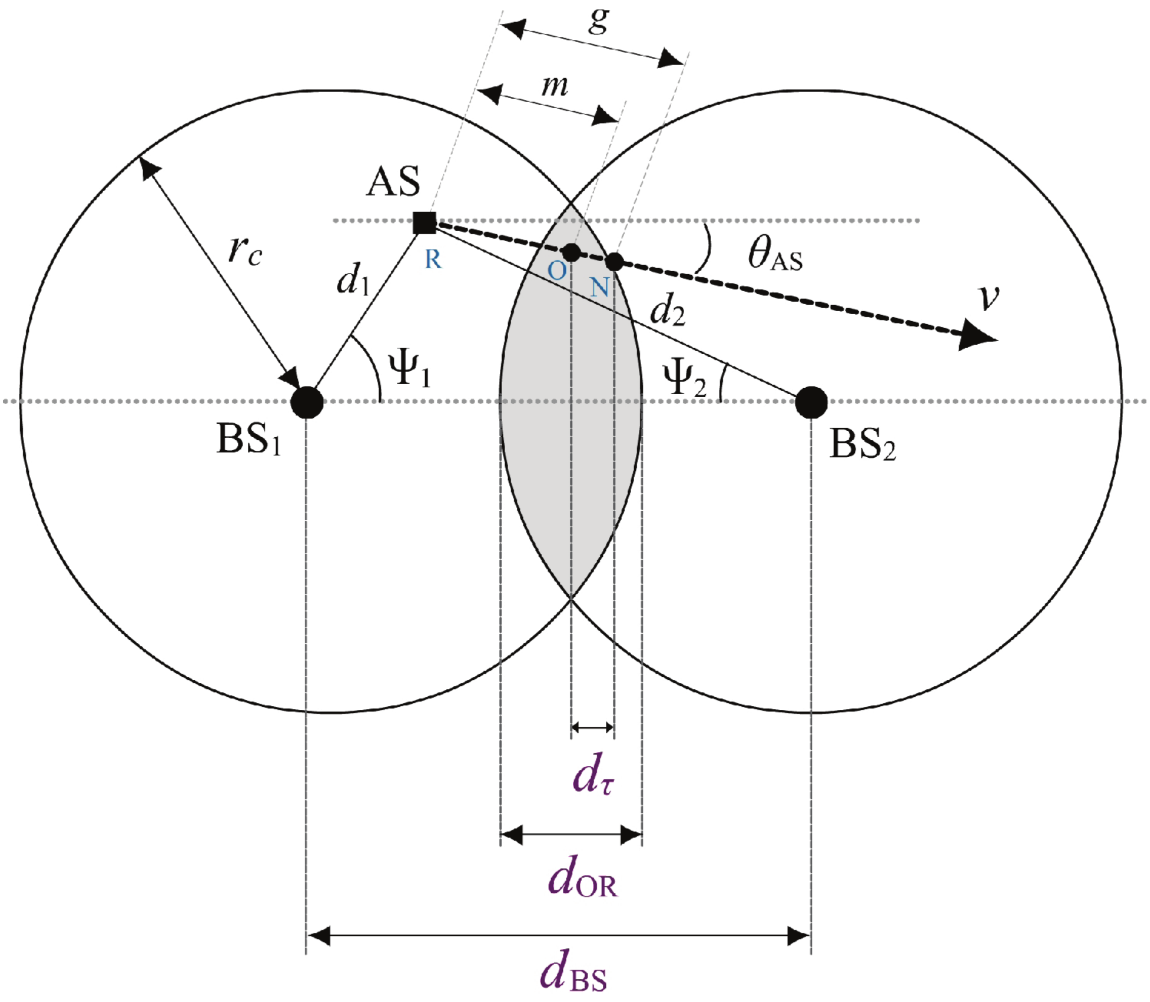


FIGURE 4.4: Top view of the land mobile Radio cellular Network.

$$\Psi_2 = \arcsin\left(\frac{d_1}{d_2}\sin\Psi_1\right) \tag{4.4}$$

The communication session is handed over by AS to a certain BS which is determined by the projected scope of AS with respect to its initial position and direction of motion, i.e., the handover from a serving BS (i.e., BS1) to a candidate BS (i.e., BS2) occurs only when the angle of AS's motion w.r.t. the line joining the serving and candidate BSs is within the angular limits of θ_{L1} and θ_{L2}, as shown in Figure. 4.5. The length of the line joining the two intersection points of overlapping cells (i.e., serving and candidate cells), can be obtained as,

$$l_{IP} = 2\sqrt{r_c^2 - \left(\frac{d_{BS}}{2}\right)^2} \tag{4.5}$$

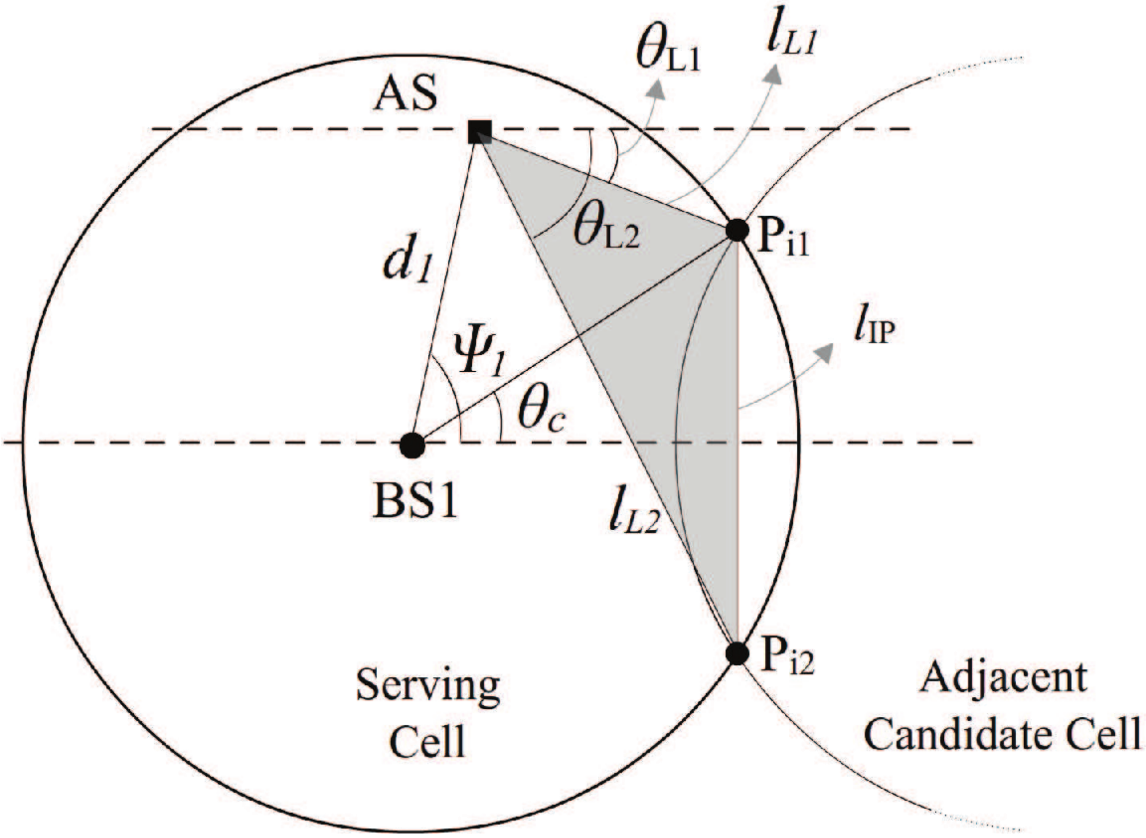


FIGURE 4.5: Handover scope of AS w.r.t. its direction of motion.

The angular limits of θ_{L1} and θ_{L2} can be easily derived and simplified as following;

$$\theta_{L1} = \arccos\left(\frac{d_{BS} - 2d_1\cos(\Psi_1)}{2\ l_{L1}}\right) \tag{4.6}$$

$$\theta_{L2} = \arccos\left(\frac{d_{BS} - 2d_1\cos(\Psi_1)}{2\ l_{L2}}\right) \tag{4.7}$$

where, the distances l_{L1} and l_{L2} (Figure. 4.5) can be found as,

$$l_{L1} = \sqrt{d_1^2 + r_c^2 - 2d_1r_c\cos(\theta_c - \Psi_1)} \tag{4.8}$$

$$l_{L2} = \sqrt{d_1^2 + r_c^2 - 2d_1r_c\cos(\theta_c + \Psi_1)} \tag{4.9}$$

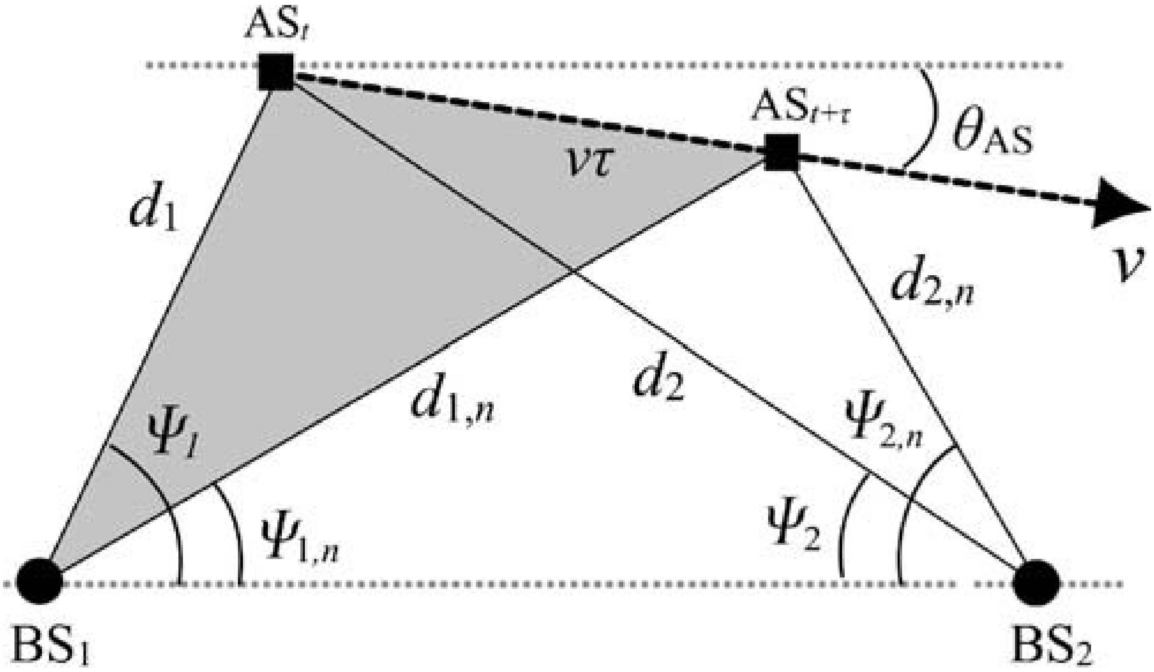


FIGURE 4.6: Mobility of AS from the serving BS towards the adjacent cell.

where, the angle, θ_c, shown in Figure. 4.5 can be found as, $\theta_c = \arccos(d_{\mathrm{BS}}/2r_c)$. The position of AS changes due to the mobility of AS (See Figure. 4.6); therefore, the new position of AS can be found in terms of velocity v, direction θ_{AS}, and the duration τ of AS's motion, as

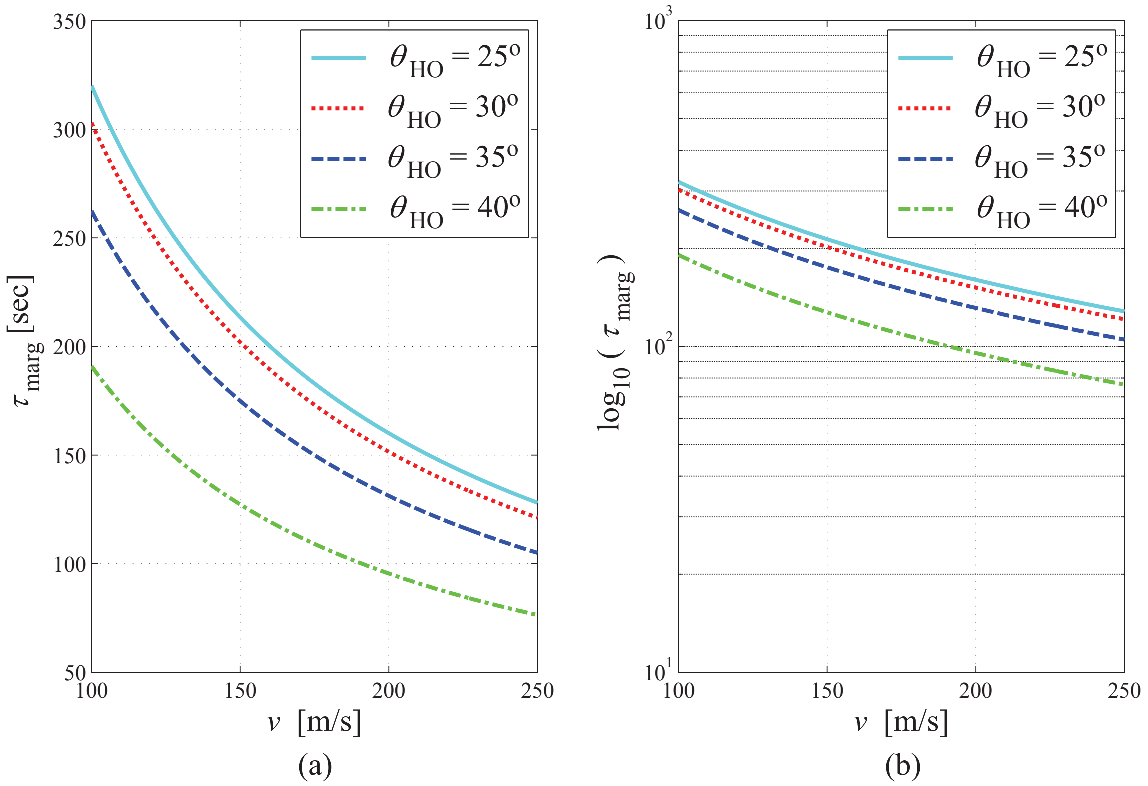
$$d_{1,n} = \sqrt{d_1^2 + (v\ \tau)^2 - 2d_1 v\ \tau \cos(\pi - \Psi_1 - \theta_{\mathrm{AS}})} \tag{4.10}$$

$$d_{2,n} = \sqrt{d_2^2 + (v\ \tau)^2 - 2d_2 v\ \tau \cos(\Psi_2 - \theta_{\mathrm{AS}})} \tag{4.11}$$

$$\Psi_{1,n} = \Psi_1 - \arcsin\left(\frac{v\ \tau}{d_{1,n}} \sin(\pi - \theta_{\mathrm{AS}} - \Psi_1)\right) \tag{4.12}$$

$$\Psi_{1,n} = \Psi_2 + \arcsin\left(\frac{v\ \tau}{d_{2,n}} \sin(\pi - \theta_{\mathrm{AS}} - \Psi_2)\right) \tag{4.13}$$

Assuming, the AS moves with a certain velocity v, and angle of motion θ_{AS} within the limits θ_{L1} and θ_{L1}, from a known initial position R at time instant t (see Figure. 4.4) and reaches the point O (point where handover is triggered) after a time delay



(a) (b)

FIGURE 4.7: The handover margin, τ_{marg}, in correspondence with velocity, v, of AS for different angles of AS's motion by using the geometrically based model, θ_{AS},($d_{\mathrm{BS}} = 500\mathrm{km}, d_1 = 100\mathrm{km}, K_2 = 40dB, \Psi_1 = 50^o$, and $r_c = 280\mathrm{km}$). (a) Shown on a linear scale (along the y-axis), (b) shown on a logarithmic scale (along the y-axis).

of m/v, and further research point N (point where handover completes) after a total time delay of, $\tau = g/v$. Thus, the time margin available to perform handover can be found as,

$$\tau_{\mathrm{marg}} = \frac{1}{v}\Big(g - m\Big) \tag{4.14}$$

The distances m and g can be found as,

$$m = \sec\theta_{\mathrm{AS}} \ \left(\frac{d}{2} - d_1 \cos\Psi_1\right) \tag{4.15}$$

$$g = -d_1 \cos(\theta_{\mathrm{AS}} + \Psi_1) + \sqrt{-d_1^2 + r_c^2 + d_1^2 \cos^2(\theta_{\mathrm{AS}} + \Psi_1)} \tag{4.16}$$

The handover margin, τ_{marg}, for different values of velocity v and direction of mobile motion θ_{AS} is shown in Figure. 4.7 for both logarithmic and linear scales, where the effects of the direction of AS motion can be observed.

4.3 Analytical Handover Model Based on Propagation Path-loss

The power received at the AS at a certain distance d_i from the i^{th} BS can be expressed in terms of the measured power, p_o, at some known distance, d_o (usually termed as the close-in reference distance) from the same BS, and path-loss exponent, n, as

$$p_{r,i}(d_i) = p_o \left(\frac{d_o}{d_i}\right)^n \tag{4.17}$$

In the logarithmic scale, (4.17) can also be expressed as,

$$p_{r,i}(d_i) = K_1 - K_{2,i}\ \log_{10}(d_i) \tag{4.18}$$

where, $K_1 = 10\ \log_{10}(p_o d_o^n)$, is a constant for the connection to each of these BSs within the network, assuming that all sea and ground BSs transmit the same power and are equipped with similar transmit and receive antennas.
$K_{2,i} = 10n$, depends on the path loss exponent, which is the environment-specific attenuation parameter [84–86] of the propagation environment between AS and i^{th} BS.

It is assumed that the power received by the serving BS on AS is denoted as $p_{r,1}$, the distance from AS to the serving BS is represented by d_1, and the predefined handover threshold with respect to the expected minimum usable received power is p_{th}. The matrix of the received power profile is defined as the matrix containing the vectors of the received power of the serving and candidate BSs, i.e.,

$$\mathbf{P}_r = [\mathbf{p}_{r,1}(d_1), \mathbf{p}_{r,2}(d_2), \ldots, \mathbf{p}_{r,M}(d_M)] \tag{4.19}$$

In a more generic form, each term in (4.19) can be represented as $\mathbf{p}_{r,i}(d_i)$, where, subscript $i = 1, 2, ..., M$ shows the M base-stations that take part in the handover procedure. Out of these M base stations, BS1 (denoted with subscript 1) is the serving BS and other $M-1$ base stations (refereed with subscript $i = 2, 3, ..., M$)

are the candidate BSs. The signal strength emanating from the base station (BS) of the serving cell and from the BSs of the neighboring cells is continuously monitored by the AS. The handover procedure is initiated when the AS traveler reaches the overlap zone between the serving cell and the neighboring cell. In the best case, the signal strength of the BS cell being served begins to weaken and the signal strength of the cell receiving AS increases, initiating the handover procedure. There are several circumstances under which cell handover can lead to several problems. Pingpong handover occurs when the signals from the cell that was previously served cause interference with the signals from the cell that is being served. Pingpong refers to the process of continuous handoff between the base station (BS) that is now connected and the BS that preceded it. This type of problem is very inconvenient because it leads to incorrect resource allocation and also reduces the overall Grade of Service (GoS) of the network. It is difficult to ensure a smooth and reliable handoff between two cells that are close to each other. The relevant handoff is initiated and overseen by AS. Thanks to the substantial processing power at AS's disposal, the implementation of any handoff technique becomes seamless. The flow of steps for handover can be simplified in a few main steps, as depicted in Figure. 4.3.

Traditionally, a mobile node needs to halt its communication with the serving BS, to measure the received power from neighboring cells. Hence, the frequency of measuring the power level from its serving and neighboring BSs is a compromise between the handover delay and the frequency of interruption of the data communication link. Given the critical importance, an extensive examination of tradeoffs and implementation intricacies in A2G and G2A communication scenarios is indispensable. In these scenarios, the Aerial Station (AS) operates without constraints on deploying multiple receivers, allowing for continuous and simultaneous monitoring of the power level across neighboring cells.

The underlying assumption is that the AS engages in an ongoing process of measuring and analyzing received pilot power from both the serving and neighboring Base Stations (BSs). This constant evaluation ensures real-time awareness of signal strength dynamics. The handover process is then activated, directing the transition to the strongest neighboring BS, precisely triggered when the power from the serving BS falls below a predetermined handover threshold. This meticulous approach ensures a seamless and efficient handover mechanism, optimizing network performance and reliability.

$$p_{r,1}(d_1) \leq p_{th} \leq \max\left(\mathbf{P}_r\right) \tag{4.20}$$

However, the fusion to this condition is not unique to each cell, as it depends on the channel conditions for a particular cell. Variations in the propagation environment can sometimes cause LoS to be unavailable for a very short period of time. This leads to fluctuations in the profile of the received power, which in turn can lead to false handover triggers. As mentioned earlier, this is the widely known ping-pong handover between the serving and candidate cells. To avoid such a scenario, a technique is proposed in [84] for land-based cellular systems that use the moving average of the previous power measurements. This paper also uses the same technique. The average power, $p_{a,i}$, from i^{th} BS can be expressed as,

$$p_{a,i}(d,w) = \frac{1}{d_w}\int_{d-d_w}^{d} p_{r,i}(x)dx \tag{4.21}$$

where $i \in \{1, 2, ...M\}$ and d_w is the averaging interval's distance. The averaging window's time interval can thus be found as $w = d_w/v$. The rest of the derivations in the paper are, thus, based on the above-mentioned time-averaged received power. The average received power matrix $\mathbf{P_a}$ can be written as

$$\mathbf{P_a} = [\mathbf{p}_{a,1}, \mathbf{p}_{a,2}, ..., \mathbf{p}_{a,M}] \tag{4.22}$$

In Figure. 4.8, the averaged received power from the serving BS and two candidate BSs is plotted. The residual power ratio vector $\mathbf{q}$ can be expressed as

$$\mathbf{q} = [q_2, q_3 ..., q_{M-1}] \tag{4.23}$$

where the residual power ratio of the i^{th} candidate BS is $q_i = (P_{a,1} - P_{a,i})$, at any time instant. A handover decision is required to be made to the BS, which provides $max(\mathbf{q})$. Let us assume the survived BS with the maximum residual power ratio denoted as $q_1 = \max\left(\mathbf{q}\right)$. The points O and N in Figure. 4.4 show the positions of

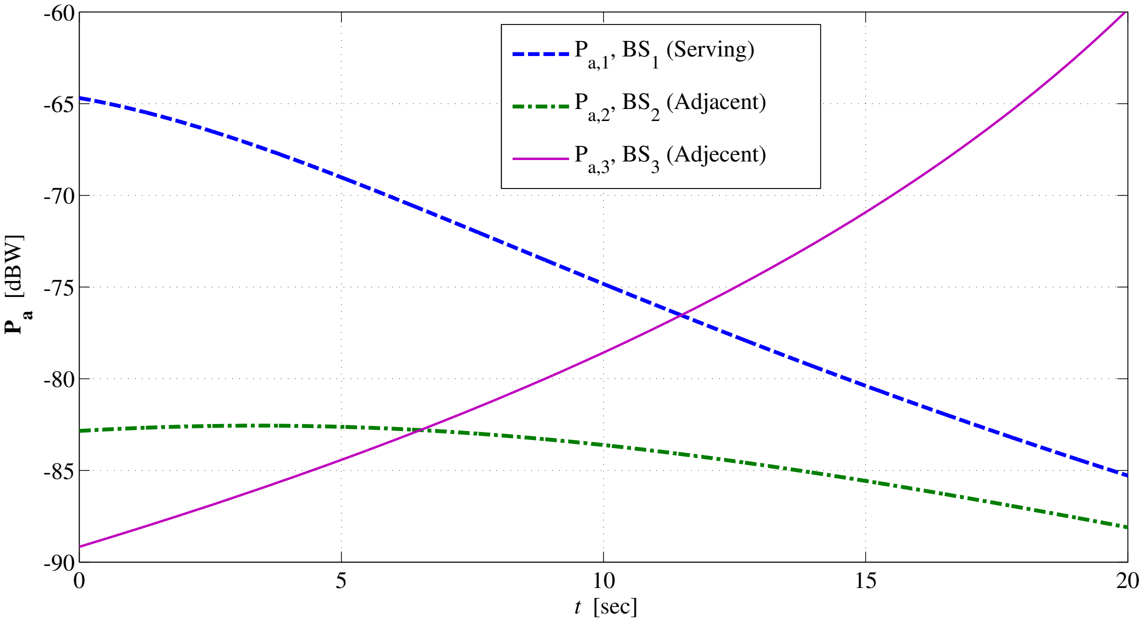


FIGURE 4.8: The averaged received power at AS from serving and adjacent candidate BSs, ($K_1 = 40dB, K_2 = 40dB, d_{\text{BS}} = 500\text{km}, d_1 = 100\text{km}, \Psi_1 = 50^o, r_c = 280\text{km}, \text{and } \theta_{AS} = 25^o$)

AS when the process of handover is triggered and when it is completed, respectively. The distance traveled by the AS from its initial position R to points O and N is shown by m and g in (4.15) and (4.16), respectively. Point O is the position of AS where the received power from BS1 and BS2 gets equal (the difference between the received powers is zero), which is

$$P_{a,2} - P_{a,1} = 0 \tag{4.24}$$

The values of $P_{a,1}$ and $P_{a,2}$ represent the power received at point O from BS1 and BS2, respectively. Rearranging (4.24) for m results in:

$$m = \frac{-d_1^2 + d_2^2}{2(d_2 \cos(\Psi_2 - \theta_{\text{AS}}) + d_1 \cos(\Psi_1 + \theta_{\text{AS}}))} \tag{4.25}$$

N is the point (Figure. 4.4) at which the difference between the received power from BS1 and BS2 gets equal to the predefined residual power ratio, q_2, which can be expressed as:

$$P_{a,2} - P_{a,1} = q_2 \tag{4.26}$$

After rearranging (4.26) for g and doing tedious calculations, the simplified form can be expressed as

$$\begin{aligned} g = \\ \tfrac{1}{10^{2q_2/K_2}-1} & \Bigg(10^{2q_2/K_2} d_2 \cos(\Psi_2 - \theta_{\mathrm{AS}}) \\ & + d_1 \cos(\alpha_1 + \theta_{\mathrm{AS}}) - \tfrac{1}{2} \Big(-4\big(10^{2q_2/K_2} - 1\big)\big(10^{2q_2/K_2} d_2^2 - d_1^2\big) \\ & +4\big(10^{2q_2/k_2} d_2 \cos(\Psi_2 - \theta_{\mathrm{AS}}) + d_1 \cos(\Psi_1 + \theta_{\mathrm{AS}})\big)^2 \Big)^{1/2} \Bigg) \end{aligned} \tag{4.27}$$

The distance, $(g-m)$, associated with the handover margin, τ_{marg}, is dependent upon the predefined residual power ratio, q_i.

The time available to complete the handover procedure is the time taken by the AS to travel the distance, $(g-m)$, with a certain velocity. Therefore, the time margin that is available to perform the handover procedure is denoted by τ_{marg} and can be obtained from the following equation:

$$\tau_{\mathrm{marg}} = \frac{1}{v}\Big(g - m\Big) \tag{4.28}$$

The required width of overlapped region between adjacent cells corresponding to a certain handover margin is shown by d_τ in Figure. 4.4, can be found as:

$$d_\tau \;=\; v\ \tau_{\mathrm{marg}}\ \cos(\theta_{\mathrm{AS}}) \tag{4.29}$$

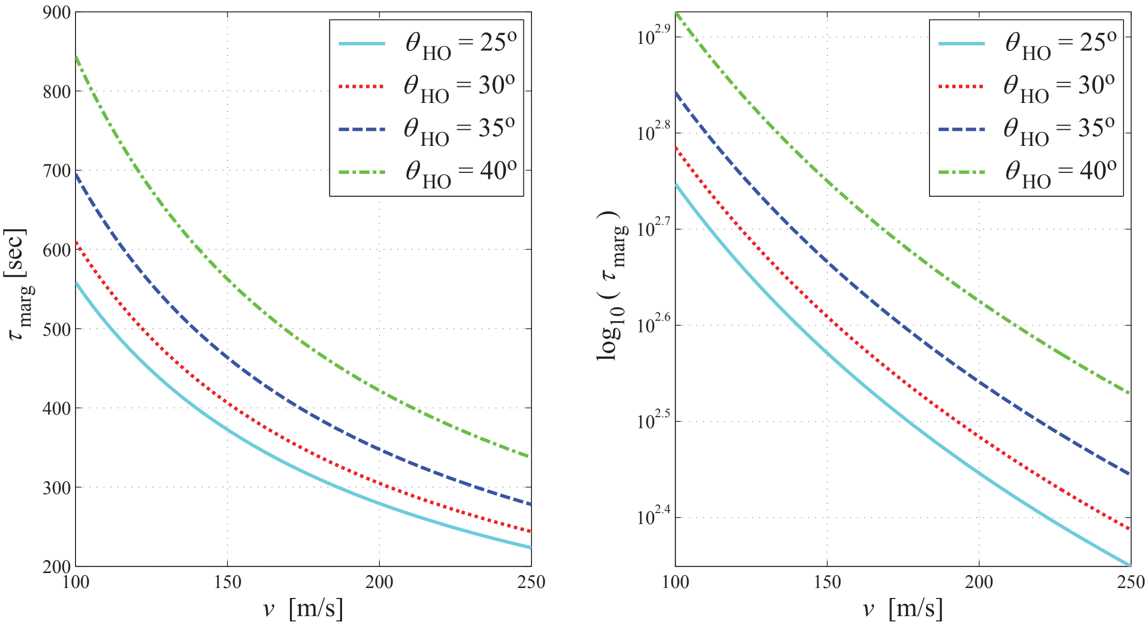
The radius of a cell, r_c, can be obtained to satisfy a certain handover time margin, as:

$$r_c = \sqrt{d_1^2 + (m + v\ \tau_{\mathrm{marg}})^2 - 2d_1(m + v\ \tau_{\mathrm{marg}})\cos(\theta_{\mathrm{AS}} + \Psi_1)} \tag{4.30}$$

The radius of a cell, r_c, can also be expressed as a function of the distance between the adjacent BSs, d_{BS}, and horizontal maximum length of the overlapped region, d_{OR}, as:

$$r_c = \frac{d_{\mathrm{BS}} + d_{\mathrm{OR}}}{2} \tag{4.31}$$

The maximum width of the overlapped region along the line joining the BS1 and BS2 is shown by d_{OR} in Figure. 4.4, which can be obtained to satisfy a certain handover



(a) (b)

Figure 4.9: The handover margin, $\tau_{\rm marg}$, in correspondence with velocity, v, of AS for different angles of AS's motion, $\theta_{\rm AS}$ by using the residual power ratio, ($q_2 = 7dB, d_{\rm BS} = 500{\rm km}, d_1 = 100{\rm km}, K_2 = 20dB, \Psi_1 = 50^o$, and $r_c = 280{\rm km}$). (a) Shown on a linear scale (along y-axis), (b) shown on a logarithmic scale (along y-axis).

margin as:

$$\begin{aligned} d_{\rm OR} &= \\ &2\sqrt{d_1^2 + (m + v\,\tau_{\rm marg})^2 - 2d_1(m + v\,\tau_{\rm marg})\cos(\theta_{\rm AS} + \Psi_1)} - d_{\rm BS} \end{aligned} \tag{4.32}$$

4.4 Handover Performance Analysis, Simulation Results and Discussion

The simulation setup involves two base stations: the serving base station (BS1) and the target base station (BS2), along with one aerial station (AS), as illustrated in Figure. 4.3. The measurements of wireless channels for the frequency range between 0.5 − 15 GHz correspond to the channel characterising parameter K_2 as between 15 − 50 dB [87]. The impact of K_2 on the handover time margin has been measured for both the uplink and downlink channels, varying from $20dB$ to $40dB$. The distance among adjacent BSs and the radius of each cell is set as $d_{\rm BS} = 500$km and $r_c = 280$km, respectively. The initial position of AS at any time t is defined as $d_1 = 100$km and $\Psi_1 = 50^o$. The initial position of AS together with its direction of motion, defines

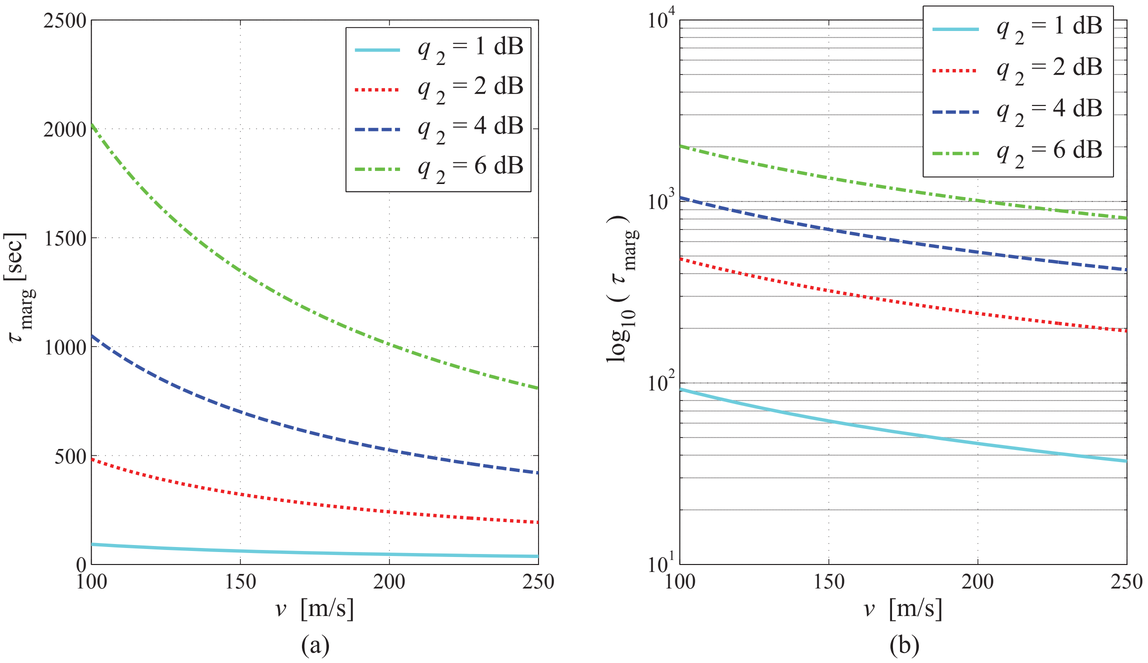


FIGURE 4.10: The handover time margin τ_{marg} in correspondence with velocity v of AS for different values of residual power ratio, ($\theta_{\text{AS}} = 45^o, d_{\text{BS}} = 500\text{km}, d_1 = 100\text{km}, K_2 = 20dB, \Psi_1 = 50^o$, and $r_c = 280$km). (a) Shown on a linear scale (along y-axis), (b) shown on a logarithmic scale (along y-axis).

the possible positions of AS at which the transfer should be triggered and performed. General scenarios for the motion of AS are considered, where AS does not move on a circular path with respect to BS nor along the line connecting the two intersections of the neighboring cells, as in Figure. 4.5.

In Figure. 4.9, the effects of different directions of motion of AS on the transfer span with respect to the velocity v of AS are shown on both linear and logarithmic scales.

At higher angles of θ_{AS}, AS moves away from the two BSs at a different velocity, so that a greater distance is required to produce the required difference q_2 between the received powers, which in turn leads to a larger handover span.

In contrast to these results, the results shown in Figure. 4.7 show exactly the opposite behavior. In the case of the model shown in Figure. 4.7, the transfer always occurs at the boundary of the serving cell. This is because the cross-sectional width of the overlapping region decreases with an increase in θ_{AS}; therefore the handoff margin decreases accordingly.

Figure. 4.10 depicts the effects of the residual power ratio on the handover margin τ_{marg} for various values of velocity v, demonstrating that as the predefined residual

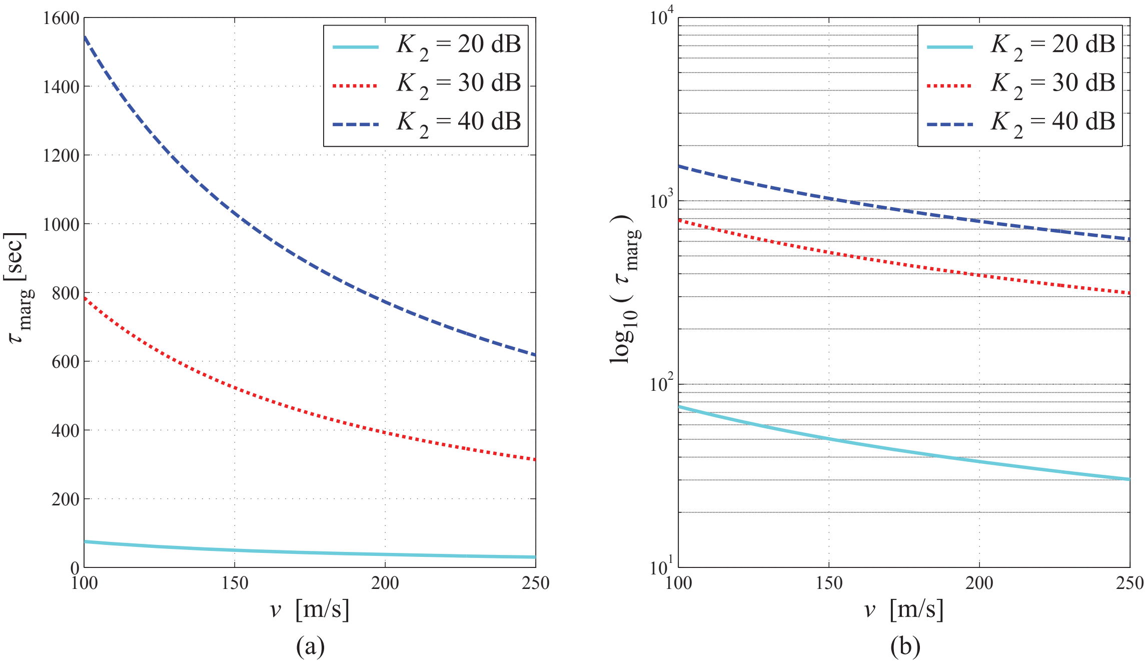


Figure 4.11: The effects of K_2 on handover margin τ_{marg} in correspondence with velocity v of AS for different values K_2, ($\theta_{\text{AS}} = 45^o, d_{\text{BS}} = 500\text{km}, d_1 = 100\text{km}, q_2 = 7dB, \Psi_1 = 50^o, \text{and } r_c = 280\text{km}$). (a) Shown on linear scale (along y-axis), (b) shown on logarithmic scale (along y-axis).

power ratio q_2 increases, so does the time span available to perform the handover. Moreover, the effects of K_2 (which contains the effects of the propagation environment) on the handover span, τ_{marg}, are shown in Figure. 4.11, where it can be observed that the handoff span decreases significantly with an increase of K_2. In other words, In dense urban areas with a higher propagation path loss exponent, the time span available for handover is smaller; therefore, the handover decision must be made faster.

QoS-constrained multimedia traffic has an acceptable delay of 50ms for handover [87], including the cost of MAC protocol signaling. This delay can be guaranteed by designing sufficiently large overlap areas of adjacent radio cells. The required width of the overlap area, d_{OR}, between two adjacent radio cells against the speed of AS is shown in Figure. 4.12, which is plotted to provide some handover time margin. The radio cells planned to support QoS-bound multimedia applications require an overlapping area of at least $72,201$m for a maximum AS speed of 300m/s.

Considering the speed of AS as 250m/s, the route of AS from the serving BS directly to the neighboring BS, and the width of the overlap region between neighboring cells

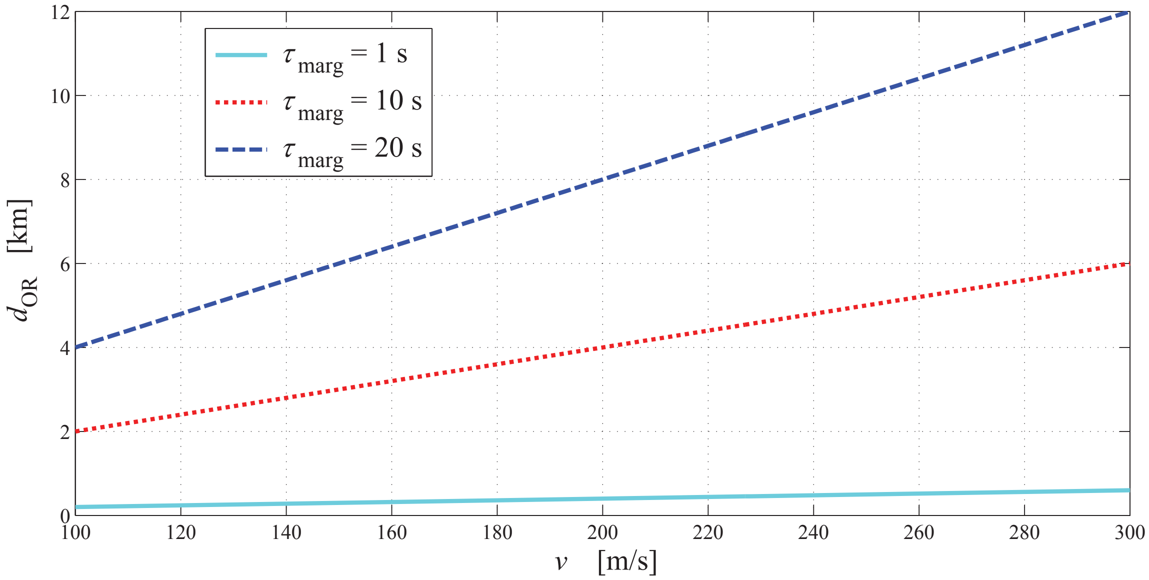


FIGURE 4.12: The required overlapping region's width, d_{OR}, against the velocity of AS, v, to ensure handover margin τ_{marg}, $(\theta_{\text{AS}} = 0^o, d_{\text{BS}} = 500\text{km}, d_1 = 0\text{km}, q_2 = 7dB, \Psi_1 = 0^o, \text{and } r_c = 280\text{km})$.

as 10km, the available time to perform the handover is 20sec, which is sufficient to perform all the tasks required for the handover.

4.5 Legal Issues of Deployment Procedure

- **International Law Understanding:** Familiarize yourself with the United Nations Convention on the Law of the Sea (Montego Bay Convention of December 10, 1982) [88]. This convention provides the primary legal framework for the laying of submarine cables, outlining the rights and responsibilities of nations in their use of the world's oceans, along with guidelines for businesses, the environment, and the management of marine natural resources.

- **Permissions Acquisition:** In the territorial sea, where the coastal state has the right to legislate and regulate the deployment of cables, ensure to obtain all necessary administrative authorizations from the competent authority for the use of the public maritime domain.

  This may involve applying for a permit from the local government or maritime authority and providing details about the proposed cable route, installation methods, and potential environmental impact.

- **Regional Guidelines Adherence:** Adhere to any regional guidelines and directives formulated by regional organizations for their member states. For example, in the European Union, guidance on best practices for the installation and protection of submarine cables is provided by the European Subsea Cables Association [89, 90].

- **Stakeholder Engagement:** Engage with all stakeholders involved, including suppliers, owners, and installers of cables, to ensure that the rights conferred and obligations imposed are clearly understood and agreed upon. This could involve regular meetings, clear communication of project goals and timelines, and collaborative problem-solving to address any issues that arise.

By following these steps, the complex legal landscape surrounding submarine optical fiber connections can be navigated, and our solution can be successfully deployed.

However, each project will have unique circumstances and challenges, so seeking legal advice tailored to the specific situation is important.

4.6 Summary of the Chapter

Chapter 4, delves into the intricate details of handover mechanisms within the envisioned airborne internet access system. Encompassing both satellite and ground-to-air (G2A) communications, the chapter establishes an Analytical Handover Model based on Cell Geometry. Augmented by an Analytical Handover Model based on Propagation Path-loss, these models undergo a meticulous examination in Section 4.4. The chapter rigorously substantiates the effectiveness of the proposed handover mechanisms through mathematical equations and exhaustive simulations. This thorough validation not only underscores the chapter's findings but also establishes the feasibility of the proposed model for delivering seamless connectivity in airborne internet access.

Chapter 5

QoS Analysis of the Proposed Airborne Internet Access Mechanism

In this chapter, a comprehensive Quality of Service (QoS) analysis of the proposed airborne Internet access schemes is undertaken. The investigation is motivated by the imperative to assess and enhance the performance of the airborne network, ensuring seamless connectivity and reliable communication for aircraft traversing diverse environments. This QoS analysis is pivotal for evaluating the efficacy of the proposed mechanisms and making informed decisions about their implementation.

The exploration begins in Section 5.1.1, where the Aerial Network Model is introduced, focusing on Point-to-Point (P2P) Aerial Networks. Subsequently, in Section 5.1.2, the discussion is extended to Aerial Ad-Hoc Networks, setting the stage for the proposed aerial network architecture detailed in Section 5.2.

Sections 5.2.1 and 5.2.2 delve into the QoS parameters, emphasizing End-to-End Delay (Section 5.3.1) and Packet Delivery Ratio (Section 5.3.2). The focus then shifts to the critical aspects of routing and reliability in the proposed work, explored in Section 5.4.

To address the unique challenges posed by airborne communication, a routing protocol for aircraft flying outside the transmission range of ground stations or sea BS is proposed in Section 5.4.1. The discussion further extends to reliability considerations in the proposed airborne Internet access mechanism in Section 5.4.2.

In Section 5.5, the outcomes of the QoS-based performance analysis are presented, and a comprehensive discussion of the results is engaged. Through meticulous evaluation and comparison of end-to-end delay (Section 5.5.1) and packet delivery ratio (Section 5.5.2), valuable insights are aimed to be provided into the effectiveness and reliability of the proposed airborne Internet access mechanisms.

5.1 Aerial Network Model

In the last two decades, air travel has become one of the most popular means of transportation, driven by rapid technological advances and the convenience it offers. Additionally, the Internet has transformed traditional postal, banking, commercial, and entertainment systems, introducing novel ways of information sharing and social networking. Consequently, airlines worldwide are incorporating Internet connectivity for their passengers. From a topological perspective, two primary network models are employed to deliver connectivity for aircraft in flight:

1) Point-to-Point (P2P) Aerial Networks and 2) Aerial Ad-hoc Networks.

5.1.1 P2P Aerial Networks

In Chapter 3, the foundational elements of the proposed airborne Internet access infrastructure were introduced, with a focus on the utilization of optical fiber technology and the integration of various communication components. As the research delves deeper, the principles established in Chapter 3 serve as the foundation for this section, which extends the analysis to address specific challenges and opportunities within the P2P (Point-to-Point) domain. The key concepts discussed earlier are revisited, and their implications in the context of enhancing connectivity within the proposed infrastructure are explored. In doing so, the way is paved for the subsequent section, Section 5.1.2, which introduces an Aeronautical Ad-Hoc approach to further expand the scope of the research. Point-to-point (P2P) communication over a network of flying airplanes stands out as one of the most common types of communication. There are several ways to establish a P2P connection. One way is ground-to-air communication (G2A) using base stations on the ground. These ground stations function like cellular towers. In most cases, beamforming is used to enable long-distance communication. Gogo Internet is one of the practical examples of G2A-based P2P communication. Communication between satellite and aircraft is also called P2P communication. This type of P2P communication is the most commonly used model for airborne communications. There are several types of satellites, including geostationary (GEO), low earth orbit (LEO), etc. Geostationary satellites provide global coverage, but also cause latency and cost issues. In contrast, LEO satellites reduce the latency problem compared to their GEO counterparts; however, they provide a much smaller coverage area than GEO satellites. In addition, a large number of LEO satellites are launched to cover specific areas on Earth. Nevertheless, increase in the number of satellites setups can be attributed to rising costs.

5.1.2 Aerial Adhoc Networks

Aerial ad hoc networks (AANs) are wireless networks that consist of a set of nodes that communicate with each other using aerial platforms, such as airplanes, drones, or balloons. AANs are often used in situations where it is difficult or impossible to deploy traditional infrastructure, such as in disaster response or military operations. In airborne ad-hoc communication is a communication model, in which the aircraft acts as a gateway, providing data to its neighbors. Data is forwarded from the gateway to the destination in a hop-by-hop manner, resulting in ad hoc networks in the air. There are several variants of such networks. For example, some of them are cluster-based semi-centralized models [45], where the cluster head is responsible for all communications. All data to/from the cluster nodes is routed through the cluster head. Another variation of the ad hoc network model is an airborne Mobile Ad-hoc Network (MANET). In MANETs, data is passed from node to node from source to destination. This type of ad hoc network does reduce latency; however, such a network is only practical in regions with dense air traffic. For example, this model fails if there is no aircraft flying near the gateway. AANs have several unique characteristics that make them different from traditional wireless networks, including mobility, deployment, range, interference, reliability, and security. AANs have the potential to provide a fast, flexible, and reliable means of communication in a variety of settings, but they also have unique challenges that must be overcome in order to be successful.

5.2 Proposed Aerial Adhoc Network

In the proposed airborne Internet access infrastructure based on submarine optical fiber, both P2P and ad-hoc models are exploited to achieve scalability and reliability. For the sake of simplicity, the solution is distributed in two parts: 1) P2P-Based Airborne Internet Access Infrastructure and 2) Aeronautical Ad-Hoc-Based Network. The details of both parts are provided in the following subsections.

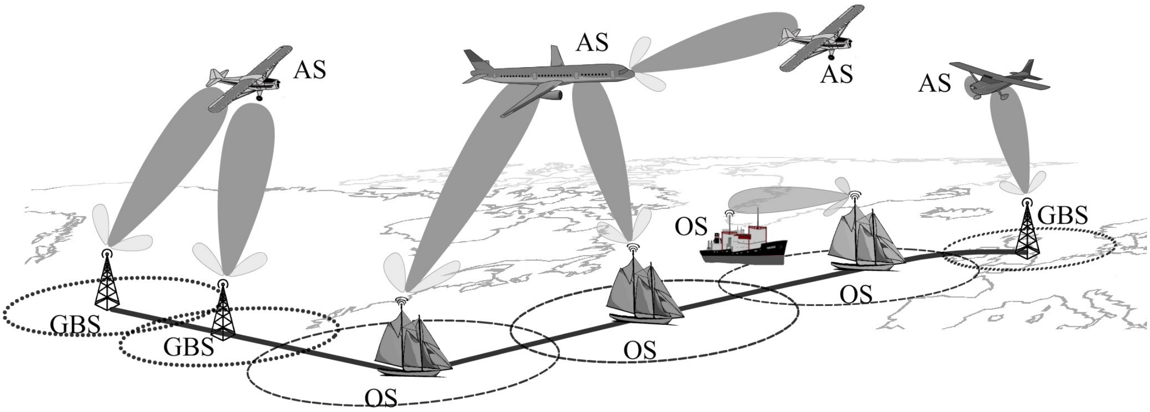


Figure 5.1: Airborne Internet provision through UOFC

5.2.1 P2P Based Airborne Internet Access Infrastructure

Chapter 3 laid the foundation for our proposed airborne internet access infrastructure, introducing key concepts such as the P2P communication model and the overarching network design. Building upon these fundamental elements, this section delves into the specifics of the proposed P2P Based Airborne Internet Access Infrastructure. This section serves as a direct extension of the principles established in Chapter 3, elucidating how the theoretical groundwork transforms into a concrete network model. Exploring the intricate details of the proposed infrastructure aims to offer a comprehensive understanding of its architecture, components, and functionality. Each aspect introduced here is a natural progression from the theoretical underpinnings outlined in the preceding chapter. Together, Chapter 3 and this section form a cohesive narrative, illustrating the evolution of our airborne internet access system from conceptualization to detailed implementation.

The overall communication model of the proposed scheme is shown in Figure. 5.1. In our solution, optical to electrical converters (on extractor) are used while extracting Internet content from the under water optical fiber cable (UOFC) and electrical to optical converters (on injector) for sending data/query to the Internet. The beamforming technique is used in data transmission between aircraft and oceanic station (OS). This not only enhances the transmission range substantially but also increases the data rate. ‘Any modern Radio Access Technology (RAT) can be used along with orthogonal frequency division multiplexing (OFDMA). The OS/GS is responsible to allocate the channel resources. Since, the existing 4G RATs (e.g, LTE, and WiMax), are OFDMA based; therefore, OFDMA is a suitable candidate for being a RAT in the current architecture. The mentioned technologies can be tailored to be appropriately used in the proposed system because the existing RAT has certain constraints. The cell radius $R_{\max}$ in the proposed solution is almost 369km as discussed in 3.4 of Chapter 3. $R_{\max}$ is enhanced in some versions of WiMax by the ranging-procedure. The existing ranging-procedure for the RAT is required to be modified for tackling the large transmission cell radius of G2A and A2G communication links. A smart scheduling algorithm could make a difference in allocating the optimal number of sub-carriers to an aircraft to achieve better QoS. Pre-existing signaling methods can be employed for communication between the FSs and the GS or OS. Given the critical importance of QoS provision, any cross-layer solution necessitates an appropriate mechanism to guarantee end-to-end delay. In the proposed solution, the QoS is maintained on different layers. For example, on the physical layer highly directional antennas are used for beamforming to enhance QoS in terms of reducing end-to-end delay and providing high data rates. Similarly, the MAC layer requires protocol ensuring required QoS while handling a huge amount of data. A recent version of WiFi is used within the aircraft to sending and receiving data to/from the onboard passengers. Moreover, on the network layer, a well-established routing protocol is essential

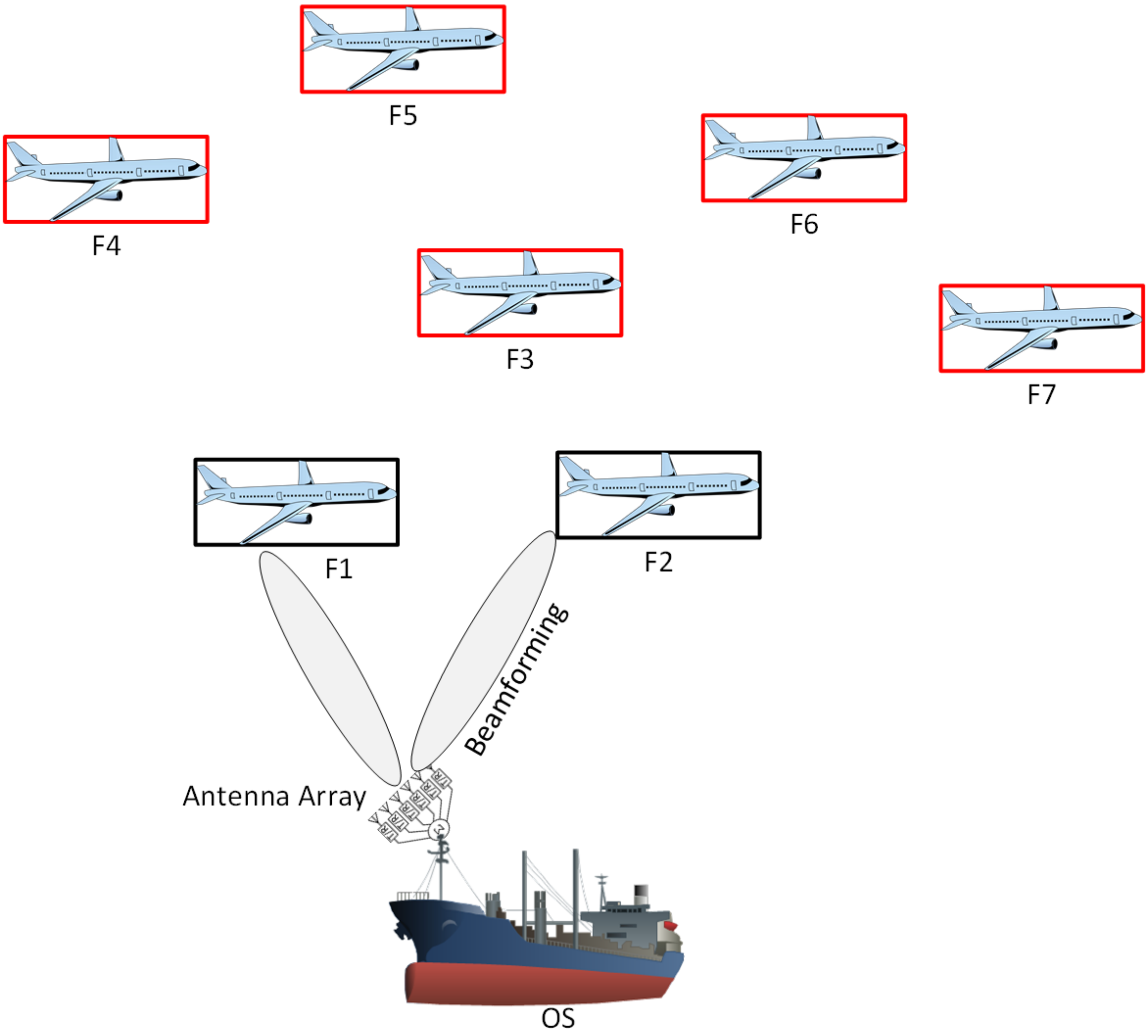


FIGURE 5.2: P2P Aerial Model.

to route the data packets optimally to ensure reliability and end-to-end delay.

5.2.2 Aeronautical Ad-Hoc Based Approach

In this approach, Internet access is provided to aircraft outside the vicinity of GS or OS. Figure 5.2 illustrates the scenario of aircraft topology in the air. The aircraft in the black rectangles are within the vicinity of at least one of the OS or GS, whereas the aircraft in the red rectangles are outside its vicinity. Consequently, providing Internet access directly to these aircraft from any of the OSs stationed in the sea is not possible.

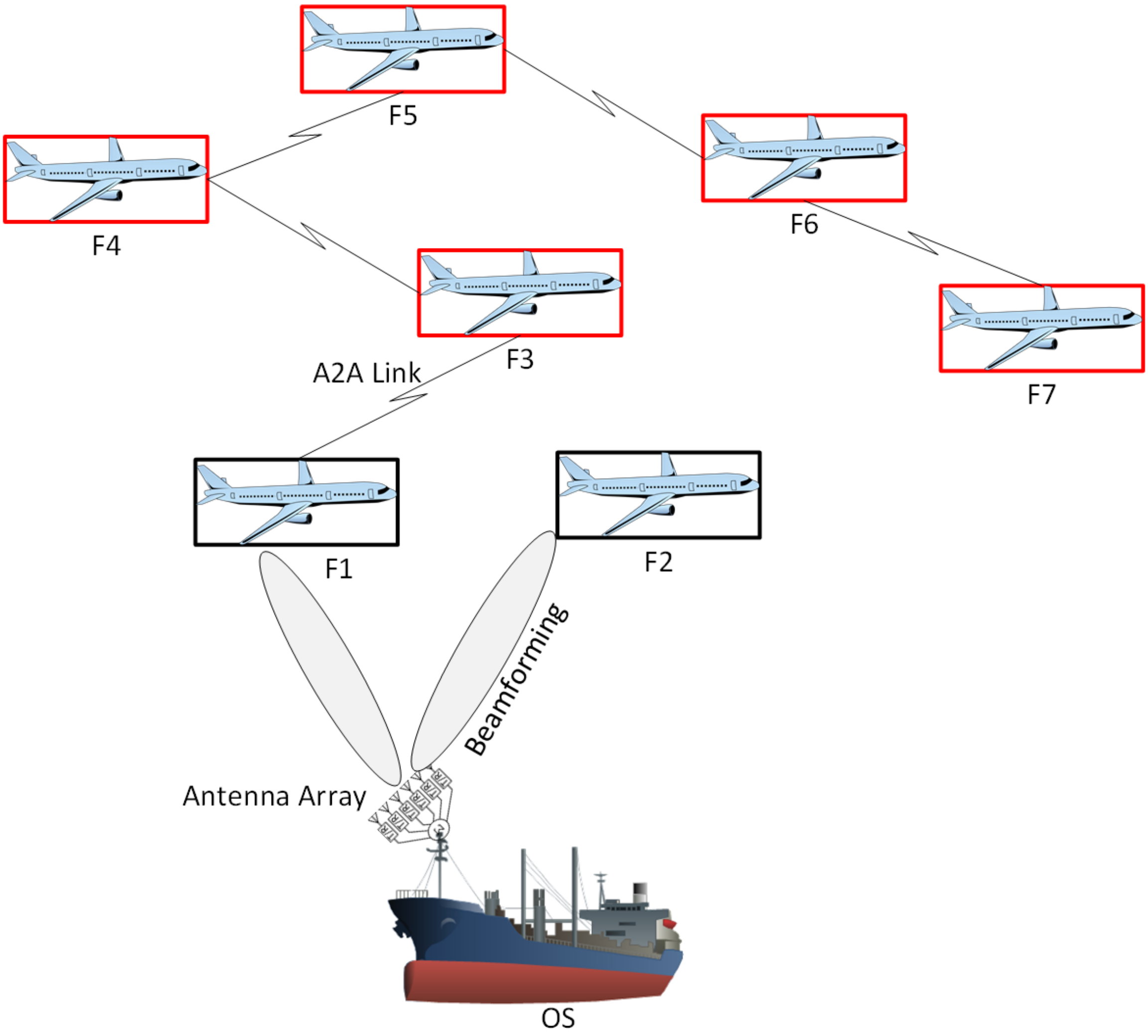


Figure 5.3: Aerial Ad-hoc Model.

In the past, the only way to provide Internet connectivity was through satellite-based Internet provision. However, the proposed scheme leverages the benefit of an existing GS or OS to provide high-speed Internet to aircraft that are not in the direct range of GS or OS. This not only reduces latency and improves the quality of service (QoS) but is also a cost-effective way to avoid expensive satellite links. Nonetheless, those out-of-range aircraft must be in the communication range of the aircraft connected with GS or OS. Figure 5.3 illustrates the architecture of an airborne ad-hoc network in the proposed methodology, where aircraft F1 is directly connected to the GS or OS. Therefore, F1 acts as a gateway for the rest of the airborne ad-hoc network. If a user from F5 requests Internet content, then that request is sent to OS (through F4, F3, F2, and F1), and in response, OS will forward the required content to F5, by selecting the recently updated optimum route (conventionally the route with minimum path

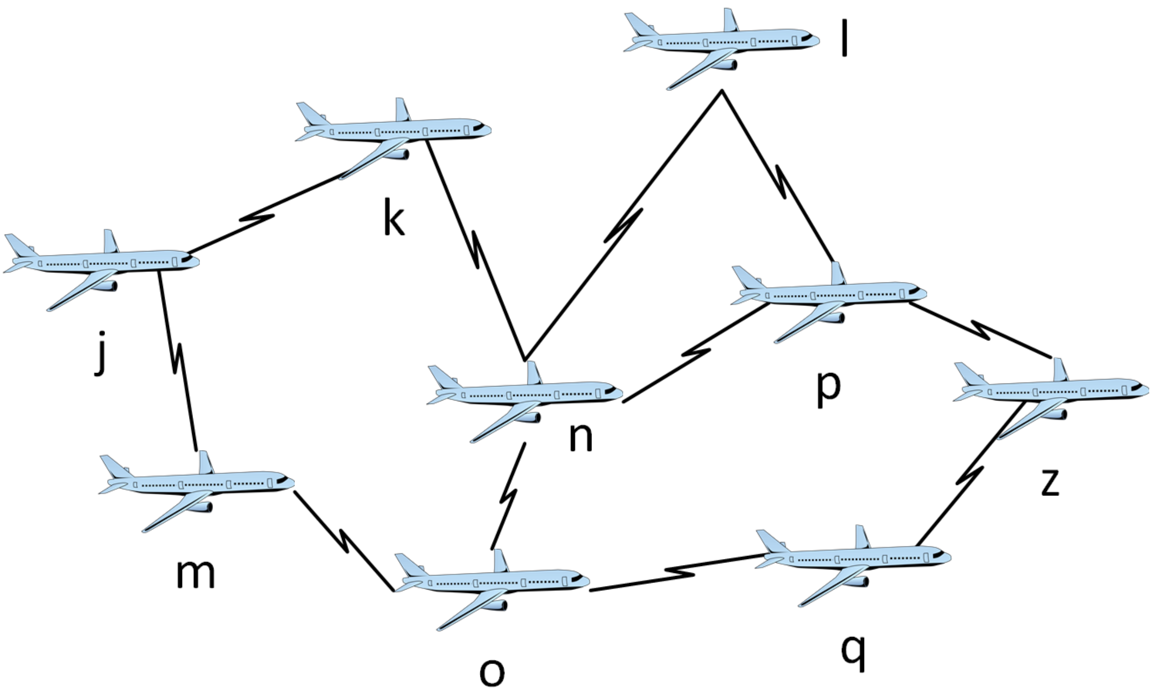


Figure 5.4: Example Scenario

cost).

In a simple scenario, the path cost is calculated through the number of hops. In the given example the route is:
$FS1 \rightarrow FS3 \rightarrow FS4 \rightarrow FS5$.

If the number of hops between the source and destination is equal, the proposed system chooses the greedy approach and forwards the packets to the next hop with the least physical distance. The least physical distance between two nodes can be calculated as follows:

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{5.1}$$

where (x_1, y_1) and (x_2, y_2) are the coordinates of the two neighbouring nodes respectively.

In the network, every aircraft/node sends a beacon message after fixed interval of time through the air-to-air (A2A) link. This beacon message contains some important information about the node including the identity N_{id} of the node, the current location L of the aircraft and its incoming and outgoing link details (I_l and O_l respectively). It is assumed that every aircraft is equipped with GPS; therefore the location of the aircraft is known. However, in airborne networks, the mobility of nodes is much higher than that in conventional ground-based ad hoc networks. In addition, because of the spherical shape of the Earth, aircraft cannot fly in a straight line but must fly along the Earth (almost in a curve). Hence, the direction of the aircraft is important. Therefore, in the proposed work, the distance between two nodes m and n is D_{mn}. Here D_{mn} is calculated by the Haversine formula as follows:

$$D_{\mathrm{mn}} = 2R_e \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_m - \phi_n}{2}\right) + \cos\left(\phi_m\right)\cos\left(\phi_n\right)\sin^2\left(\frac{\lambda_m - \lambda_n}{2}\right)}\right) \tag{5.2}$$

where R_e is the radius of the Earth, ϕ_m, ϕ_n are the latitudes and λ_m, λ_n are the longitudes of the two nodes m and n, respectively [91].

The transmission power of 57.8dBm is required to provide full coverage to R_{max}. Moreover, the average speed of a commercial aircraft is almost 725 km/hr [92]. Therefore an aircraft will remain connected with one oceanic station is calculated as:

$$T_{\mathrm{con}} = \frac{S_a}{R_{\mathrm{cell}}} \tag{5.3}$$

Whereas, T_{con} is the total time of an aircraft connected with an OS, S_a is the speed of an aircraft, and R_{cell} is the coverage range of an OS. Hence the total time of an aircraft connected with an OS calculated through the above equation is approximately 0.98 hours (58 minutes and 48 seconds). Therefore, an onboard passenger can avail of high-speed Internet connectivity for almost an hour.

5.3 QoS Parameters

The quality of service (QoS) can be defined as "a set of service requirements that the network must satisfy when transporting a packet stream from a source to its destination" [93]. In other words, QoS is the level of performance of a service that the network provides to the user. QoS provisioning aims to achieve more deterministic network behavior so that information transmitted over the network is better delivered and network resources are better utilized. The network is expected to provide subscribers (in our case, the airborne users) with a set of predetermined, measurable performance characteristics, such as delay, throughput, etc. QoS for a network is measured by the assured amount of data that a network transmits from one location to another in a given time window. The size of the network is directly related to the quality of service. If the network is extensive, the network control problem can be challenging. Not all routes can provide the same quality of service to meet user requirements. In the proposed architecture, the Internet is provided on the aircraft through beamforming, and Internet QoS is intended for the subscribers on the aircraft. As mentioned earlier, QoS parameters usually depend on the context of the applications involved. Different applications or end systems may have different interpretations of their QoS requirements. However, the following parameters can be considered the basis for our Internet QoS deployment since the other parameter variables can also be mapped to them.

The QoS parameters intended for use in the analysis are explained in the following lines:

5.3.1 End-to-End Delay

It is the time that elapses from the departure of a data packet from the source node to its arrival at the destination node, including queuing delay, switching delay, propagation delay, etc. In our technique, a one-way delay is when the data is sent from the ship and when it arrives at the subscribers on the plane. Measuring one-way delay is usually tricky due to clock synchronization issues.

Sometimes the round-trip delay is used instead as an indicator of the delay boundary, but because of the typical round-trip on the Internet, this may not give a good indication of the delay parameter. In our case, however, this is not the case since the outbound and return paths to and from the aircraft and ship stations are identical.

5.3.2 Packet Delivery Ratio

Depending on the type of routing protocol used in a network, it is paramount to determine the packet delivery ratio so that the performance of the routing protocol can be evaluated. As part of the simulation process, several parameters are chosen to evaluate how well the protocol functions in real life. Factors such as the size of the packet, the number of nodes, the distance of the transmission, and the structure of the network itself are crucial in determining the packet delivery rate. A packet delivery ratio also called a packet delivery rate, is the percentage of data packets that reach their destination out of the total number of packets sent.

Another way to define packet delivery ratio is the ratio between the number of packets received at the target and the number of packets sent from the source in a given amount of time. The packet delivery ratio of a system is one of the factors that contribute to increasing the performance of the system.

5.4 Routing and Reliability in P2P and Ad-Hoc Aerial Networks

In this section, algorithms for the routing and reliability of networked data are proposed. These algorithms are necessary to find QoS parameters in P2P and ad hoc areal networks. The determined QoS parameters are then used in the next section to perform a QoS analysis of the proposed airborne Internet access architecture.

5.4.1 Proposed Routing Protocol for Airborne Internet Access for the Aircraft Flying Outside the Transmission Range of OS

Because of the special characteristics of an airborne ad hoc network, our solution must take into account many factors. The relative distance (in terms of packet forwarding) can be expressed as P_{sd}, where s is the current node and d is the neighboring node (to which the packet is to be forwarded). P_{sd} can be illustrated with an example given in Figure. 5.4.

Consider a packet with destination z arriving at node m. If the packet is forwarded to node n, the relative distance (P_{mn}) between nodes m and n can be calculated as follows:

$$P_{\mathrm{mn}} = D_{\mathrm{mz}} - D_{\mathrm{nz}} \tag{5.4}$$

where, D_{mz} is the distance between the current intermediate node m and the final destination node z, and D_{nz} is the distance between the nearest neighbor node n and the node z. In the proposed solution, geographic forwarding is utilized, forwarding the packet to the neighbor node with the least distance to the destination node.

The above forwarding procedure in the airborne ad hoc routing algorithm is explained in the Algorithm 5.1.

5.4.2 Reliability in Proposed Airborne Internet Access Mechanism

As nodes move at high speed in the proposed mechanism, there is a possibility that reliability may become an issue. For this purpose, a solution is proposed based on efficient controlled flooding to increase the probability of packet delivery success and to prevent packet loss as a result of unstable paths due to high mobility. With efficient flooding, it means that each packet is not forwarded to all nearby nodes, but rather to one, two, or three nearby nodes based on three thresholds i.e., α, β, and γ.

In other words, neighbors are classified as the best neighbors, the second-best neighbors, and the third-best neighbors. To determine whether the packet is redundantly forwarded, the packet drop ratio P_{drop} needs to be considered. The optimal neighbor can be chosen based on one of the following equations:

$$BP_{\mathrm{mz}} = \underset{n \in N}{max}\{P_{\mathrm{mn}}\}, P_{\mathrm{mn}} > 0. \tag{5.5}$$

$$SBP_{\mathrm{mz}} = \underset{n \in N}{secondmax}\{P_{\mathrm{mn}}\}, P_{\mathrm{mn}} > 0. \tag{5.6}$$

$$TBP_{\mathrm{mz}} = \underset{n \in N}{thirdmax}\{P_{\mathrm{mn}}\}, P_{\mathrm{mn}} > 0. \tag{5.7}$$

where, BP_{mz}, SBP_{mz} and TBP_{mz} are used to identify the neighbor node for the best forwarding path, the second-best forwarding path, and the third-best forwarding path, respectively. N is the set of all nodes in the ad hoc network, while max, second max, and third max are the maximum, second maximum, and third maximum of P_{mn}, respectively. When a packet is adaptively forwarded on more than one path, this increases the probability of successful delivery from a source m to a destination z.

A simple example is presented in Figure. 5.2 and 5.3 to illustrate the procedure of the proposed scheme (both in point-to-point and ad-hoc scenarios). The procedure can be illustrated with an example. Suppose two adjacent nodes j and m. Here, a packet arrives at node m from source j. It is now necessary to calculate the distances based on the proposed solution using Equation 5.2, (where N represents the set of all forwarding neighbors) from the current node to all forwarding neighbors (in this case, N comprises o and n).

During the next phase, the relative distances P_{mo} and P_{mn} are calculated using (5.4), which are then used to calculate the top three best paths using (5.5), (5.6) and (5.7) respectively, as encoded in Algorithm 5.2. The entirety of the proposed solution is encapsulated and illustrated in the flowchart presented in Figure 5.5. This comprehensive visual representation serves as a guide, delineating each step and component of the proposed solution in a coherent and systematic manner. The flowchart acts as a roadmap, allowing a clear and structured understanding of the entire solution, from its inception to the culmination of processes. By following the sequential progression outlined in the flowchart, stakeholders can gain valuable insights into the intricacies and interactions embedded within the proposed solution, facilitating a comprehensive comprehension of its functionality and operational workflow.

5.5 QoS Based Performance Analysis and Results' Discussion

In the simulation setup, one ground station (GS) is considered, located at the seashore, to make the scenario comparable to that of the existing work. The said GS acts as an Internet gateway as shown in Figure. 5.1. The detailed simulation

Algorithm 5.1 Airborne Ad-Hoc Routing Algorithm

```
Input: Location of source node $j$,Hello message $H_m$, Hello Response $H_{\text{res}}$, Relative distance $P_{\text{mn}}$, Current Node $m(m_x, m_y)$, Destination Node $z(z_x, z_y)$, Maximum possible neighbors of node is $Max_N$, Neighbour set $N$, Location of all $N$ i.e. $N(N_x, N_y)$; Angular Distance $D_{\text{mn}}$, Relative Distance $P_{\text{mz}}$
Output: Best path $BP_{\text{mz}}$, Second Best Path$SBP_{\text{mz}}$ and Third Best Path $TBP_{\text{mz}}$
    $j$ sends $H_m$ containing $I$, $L$, $I_l$, $O_l$.
if Any node $i$ receives $H_m$ then $N_i$ send $H_{\text{res}}$ Where $i$={1,2,3,....$Max_N$} and $i \in N$ calculate $D_{\text{mn}} \forall N$
Store $D_{mn}$ in a table $T_d$
Calculate $P_n^{N_i}$ from $N$ to next node $n$
Calculate $BP_{\text{mz}}$, $SBP_{\text{mz}}$ and $TBP_{\text{mz}}$
Packets will be forwarded to either $BP_{\text{mz}}$, $SBP_{\text{mz}}$, or $TBP_{\text{mz}}$ based on the Algorithm. 5.2
else No Path found
```

Algorithm 5.2 Reliability

```
Input: $\alpha$, $\beta$, $\gamma$, Packet drop ratio $P_{\text{drop}}$
Output: Execute Algorithm. 5.1
if $P_{\text{drop}} < \alpha$ then Source send packets to $BP_{\text{mz}}$
else
    if $P_{\text{drop}} > \alpha$ and $P_{\text{drop}} < \beta$ then Source sends packets to two neighbors $BP_{\text{mz}}$ and $SBP_{\text{mz}}$
    else
        if $P_{\text{drop}} > \beta$ and $P_{\text{drop}} < \gamma$ then Source sends packets to three neighbors $BP_{\text{mz}}$, $SBP_{\text{mz}}$ and $TBP_{\text{mz}}$
        else Restart the algorithm
```

setup is given in Table 5.1. One hundred aircraft are considered to be flying simultaneously over the North Atlantic Corridor (NAC) with a maximum transmission range of 200 km and a data rate of 50 Mbps. Two different scenarios are considered for the simulation. In the first scenario, the aircraft are flying randomly on different routes, while in the second scenario, a few aircraft are selected to fly with pre-defined routes. The QoS performance of our proposed Airborne Ad-hoc Routing Algorithm (AARA) is compared with several well-known airborne routing algorithms, including Geographic Load Share Routing (GLSR) [66], A Cross-Layered Routing Approach for Civil AANET A-LSR [94], and Geographic Routing for AANET (GRAA) [95]. To evaluate the performance of the proposed AARA, multiple simulation rounds were conducted using the network simulator ns-3 to assess end-to-end delay and packet delivery ratio as the evaluation parameters.

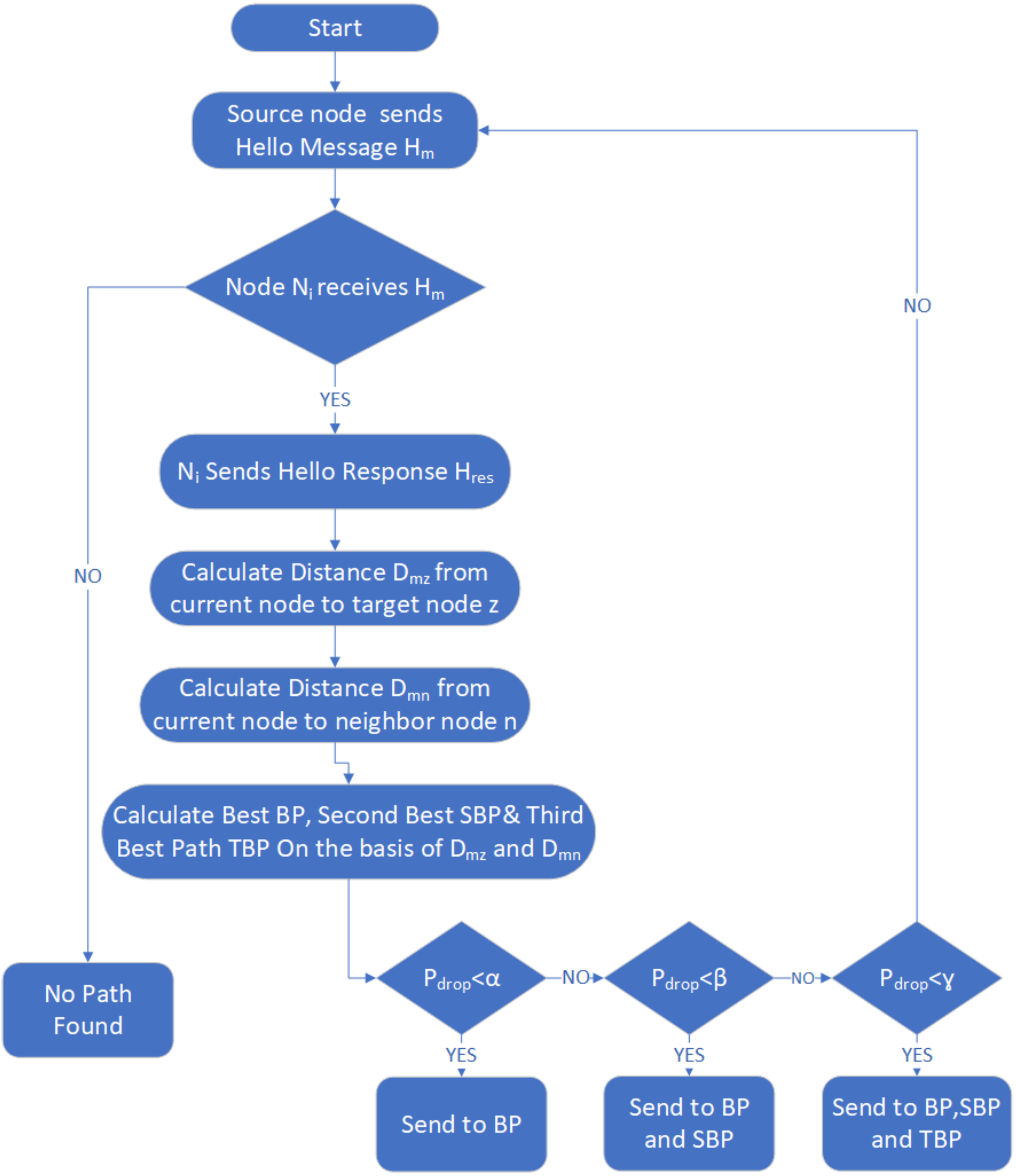


FIGURE 5.5: Flowchart of Proposed AARA

5.5.1 End-to-End Delay

in this section, the behavior of the end-to-end delay of the proposed solution is compared with that of the existing solutions. Figure. 5.6 shows the effect of the number of nodes on the end-to-end delay for randomly flying aircraft while considering the proposed algorithm along with the existing solutions. Whereas, Figure. 5.7 demonstrates the impact of number of hopes in semi ideal scenario on end-to-end delay. The detailed analysis is discussed in the following sections.

Table 5.1: Simulation Setup

Parameters	Values
Area	NAC
Nodes	100
Link data rate	50 Mbps
Simulation Rounds	100
A2A communication Range	200 km
Simulator	ns-3

5.5.1.1 End-to-End Delay Comparison in Case of Random Scenario

The simulation results, as illustrated in Figure 5.6, provide a nuanced perspective on AARA's performance in a dynamic scenario where 100 aircraft are randomly positioned over a 1000 km range. Despite the introduction of unpredictability in aircraft direction, AARA maintains its overall advantage in end-to-end delay compared to existing schemes (ALSR, GLSR, and GRAA), albeit with a slightly reduced margin. This reduction suggests that network factors such as congestion and interference play a more substantial role in this dynamic setting.

Upon closer analysis, AARA's resilience and scalability in the face of network dynamics become evident. It consistently exhibits the lowest delay across all hop counts, showcasing its adaptability to network changes and its ability to optimize routing even with randomly positioned nodes. At the highest hop count (node 100), AARA demonstrates a significant 37% reduction in delay compared to ALSR, 20% compared to GRAA, and 10% compared to GLSR.

This sustained advantage highlights the effectiveness of AARA's dynamic routing mechanisms. Its proactive approach and capability to minimize unnecessary hops remain valuable even in the absence of direction information. Furthermore, AARA's robustness is evident in its ability to handle network congestion caused by the random topology, maintaining lower delay than other schemes. The figure underscores that the difference in end-to-end delay is not significant when the number of nodes is small, but it increases as the aerial network expands. It is clear from the results that the proposed solution AARA outperforms the rest of the three solutions in terms of delay by a large margin.

In the case of a random path, GLSR, GRAA, and A-LSR required well above 300 ms of end-to-end delay for 100 aircraft. This delay is considered unacceptable for many modern real-time services and applications, such as online cinema and online games. Conversely, the proposed AARA had an end-to-end delay of only 231 ms, representing a significant difference of more than 130 ms. This positions AARA as a suitable candidate for many modern real-time applications and services.

As described in the preceding lines, another scenario is also considered where a specific predefined air traffic route is chosen. This comprehensive analysis collectively highlights AARA's robustness, efficiency, and suitability for providing high-speed internet access to aircraft in diverse network configurations, paving the way for exciting advancements in airborne communication.

5.5.1.2 End-to-End Delay Comparison in Case of Pre-Defined Scenario

The simulation results, as depicted in Figure. 5.7, provide comprehensive insights into the superior performance of our proposed Airborne Ad-hoc Routing Algorithm (AARA) for delivering high-speed internet access to aircraft flying over vast oceans. AARA consistently outperforms the compared schemes (ALSR, GLSR, and GRAA) in terms of end-to-end delay, showcasing its scalability and efficiency across a spectrum of hops, with 100 km increments up to a total distance of 1000 km.

While all schemes experience increased delay with additional hops due to routing overhead, AARA distinguishes itself with a notably smaller delay increase. This can be attributed to its proactive and predictive routing approach, allowing it to anticipate optimal paths and minimize unnecessary hops, in contrast to the reactive nature of ALSR or the hop-minimization focus of GRAA.

Moreover, AARA's consideration of aircraft direction and mobility provides an edge over GLSR's, especially when aircraft share a common direction. Delving into specific statistics, the simulation results highlight AARA's remarkable efficiency.

At the highest hop count (10 hops), AARA exhibits a significant 53% reduction in average end-to-end delay, consistently maintaining at least a 20% delay reduction compared to all other schemes across the entire range. These reductions translate into tangible benefits for passengers, ensuring smoother streaming, faster browsing, and more responsive communication even in flights extending further into the ocean.

A closer examination of the results reveals key factors contributing to AARA's success. Its proactive and predictive routing approach, anticipating optimal paths and minimizing unnecessary hops, significantly contributes to the observed lower delay. Specifically, considering the provided data in milliseconds:
At 10 hops, the end-to-end delay for AARA is 191 ms, compared to 254 ms for ALSR, 240 ms for GLSR, and 297 ms for GRAA.

Additionally, AARA's consideration of aircraft direction and mobility proves advantageous, demonstrated by its consistent 15% lower delay compared to GRAA, which focuses solely on hop minimization and might lead to less efficient paths for aircraft flying in the same direction.

These combined architectural and statistical perspectives underscore AARA's prowess in furnishing fast and reliable internet access for highly mobile aircraft, even in remote oceanic expanses.

The consistent superiority in end-to-end delay positions AARA as a compelling solution for revolutionizing in-flight communication, unlocking diverse possibilities for aerial applications.

Hence, it can concluded that AARA performs much better than the well-known solutions in terms of end-to-end delay while considering both scenarios.

5.5.2 Packet Delivery Ratio

Packet delivery ratio (PDR) is a crucial quality of service (QoS) parameter that measures the percentage of packets successfully transmitted from a source to a destination. A high PDR is essential for ensuring reliable data communication in various wireless networks, including aircraft networks. In aircraft networks, the mobility of

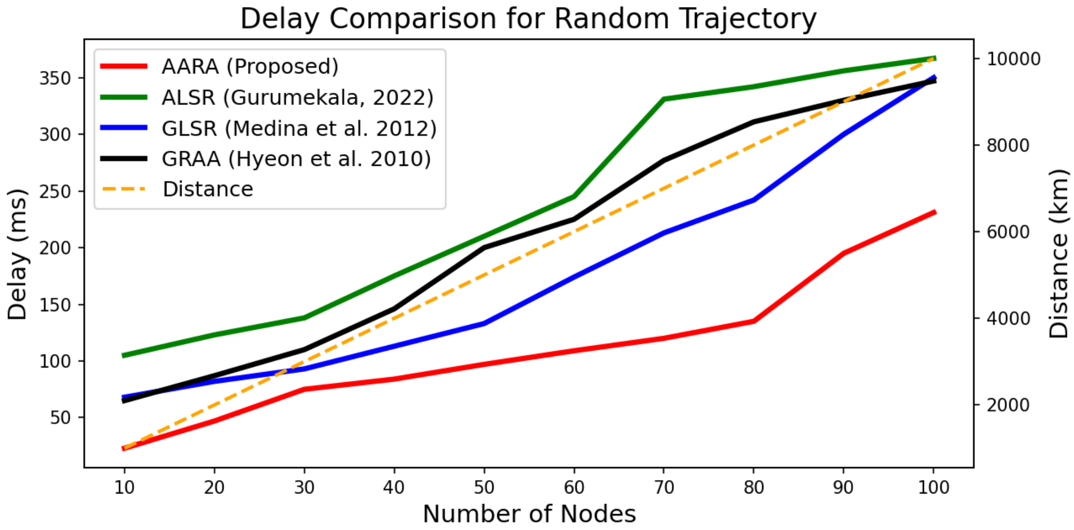


FIGURE 5.6: Delay comparison of aircraft flying on random paths.

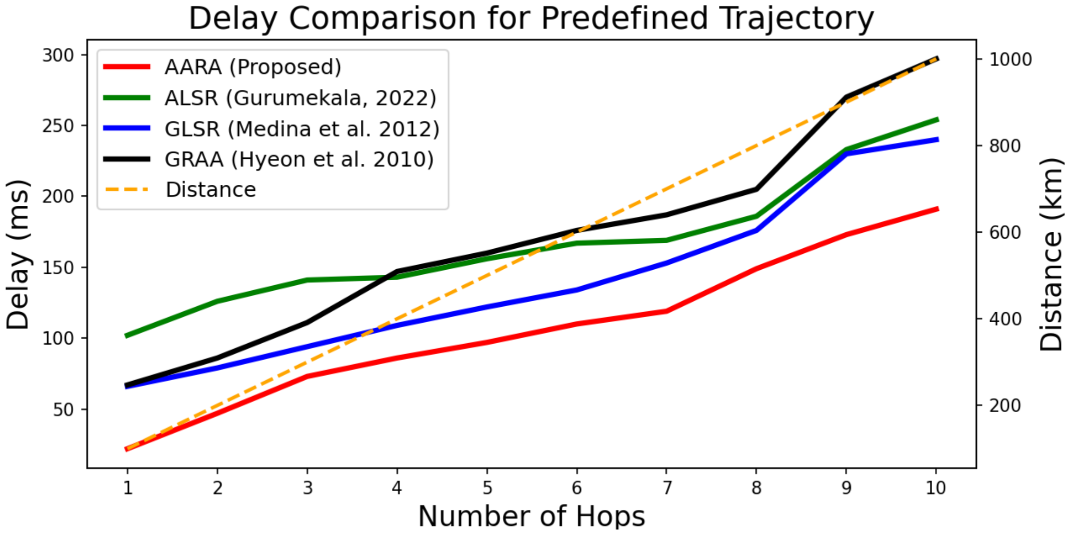


FIGURE 5.7: Delay comparison of aircraft flying on a predefined path

nodes is significantly higher compared to other network scenarios, posing a significant challenge to maintaining a stable and reliable PDR. Several factors influence the PDR in aircraft networks, including node mobility, network size, and network topology. The dynamic nature of aircraft networks, with nodes constantly changing position and relative distances, can lead to increased packet loss due to signal attenuation, interference, and link disruptions. Additionally, the sheer size of aircraft networks, spanning vast distances and involving a large number of nodes, can further complicate packet delivery, particularly when dealing with real-time applications that demand high throughput and low latency. Among the various routing protocols proposed for aircraft networks, AARA stands out for its superior PDR performance.

Unlike other schemes like GLSR, GRAA, and A-LSR, AARA establishes paths that utilize both stationary ships connected via underwater optical fiber cables (UOFC) and moving aircraft. This hybrid approach allows AARA to leverage the stability of UOFC to maintain high PDR even in the presence of highly mobile nodes.

5.5.2.1 PDR Comparison in Random Scenario

The analysis of Packet Delivery Ratio (PDR) in the context of an aerial ad-hoc network covering a total distance of 1000 km, with aircraft randomly flying varying distances, reveals intricate patterns in the performance of routing algorithms—AARA, ALSR, GPSR, and GRAA as shown in Figure. 5.8. The spatial distribution of nodes, where fewer nodes indicate proximity to the gateway aircraft and more nodes imply a dispersed layout, adds a crucial layer to the discussion. AARA consistently emerges as the frontrunner in PDR across different node counts. At 10 nodes, AARA achieves an impressive PDR of 94%, outshining ALSR (85%), GPSR (95%), and GRAA (85%). This superiority extends as the network grows, with AARA maintaining a robust PDR of 83% at 100 nodes, showcasing its adaptability even in scenarios where nodes are dispersed over the 1000 km total distance. The concentration of nodes near the gateway aircraft is reflected in AARA's efficiency, especially evident at lower node counts. The proactive and predictive routing approach of AARA contributes to its consistent high PDR, demonstrating its resilience in scenarios where aircraft are randomly positioned but concentrated closer to the gateway.

Conversely, ALSR, while displaying reliability, falls short of AARA's PDR. At 100 nodes, ALSR records a PDR of 77%, indicating potential challenges in scenarios where some nodes are positioned significantly farther away. This suggests a need for further optimization to enhance ALSR's efficiency, particularly in scenarios with a dispersed spatial distribution of nodes. GPSR exhibits fluctuations in PDR, especially noticeable as the network expands.

At 100 nodes, GPSR records a PDR of 75%, indicating potential challenges in maintaining efficient packet delivery in scenarios with dispersed nodes. The geographic-based approach of GPSR may face limitations in adapting to changing spatial dynamics. GRAA consistently lags behind other algorithms, with a PDR of 70% at

100 nodes. This lower PDR highlights challenges in GRAA's routing strategies, especially in scenarios with a dispersed layout. The impact of spatial distribution becomes pronounced, suggesting a need for refinement in GRAA's approach.

In-depth analysis further underscores AARA's versatility. It consistently outperforms or equals the best PDR achieved by other algorithms, showcasing its reliability in ensuring successful packet delivery. The spatial distribution of nodes accentuates the adaptability of AARA, making it a promising solution for diverse airborne applications.

These findings highlight the interplay between routing algorithms, spatial distribution of nodes, and the dynamic nature of airborne ad-hoc networks. The discussion provides valuable insights into the challenges and strengths of each algorithm, setting the stage for future research to explore optimization strategies and enhance the efficiency of routing algorithms in scenarios with varying spatial distributions.

In conclusion, PDR plays a pivotal role in evaluating the performance of aircraft networks, given the dynamic and challenging environment in which they operate. AARA's ability to maintain a high PDR, even in the presence of highly mobile nodes, makes it a compelling solution for ensuring reliable data communication in aircraft networks.

5.5.2.2 PDR Comparison in Pre-defined Scenario

As demonstrated in and Figure 5.9, in the semi-optimal scenario where nodes are spaced 100 km apart and traveling in almost the same direction, the analysis of PDR trends for AARA, ALSR, GLSR, and GRAA reveals insightful patterns.

AARA consistently demonstrates robust PDR performance across various hop counts. Starting at 94% for 1 hop, AARA maintains a high level of packet delivery efficiency, gradually declining to 86% at 10 hops. This decline is relatively modest, suggesting that AARA's proactive routing approach effectively copes with the challenges of semi-optimal scenarios, even with increased network complexity.

ALSR shows a gradual decline in PDR as the number of hops increases. Commencing at 85% for 1 hop, ALSR experiences a decrease, reaching 78% at 10 hops. The decline in PDR indicates potential limitations in ALSR's adaptability to semi-optimal scenarios with a higher number of hops.

GLSR exhibits competitive performance, maintaining adaptability to the semi-optimal configuration. Starting at 95% for 1 hop, GLSR records a PDR of 77% at 10 hops. This suggests that the grid-based approach aligns effectively with the spatial characteristics of closely spaced nodes, even with an increasing number of hops.

GRAA displays a declining trend in PDR across various hop counts. Beginning at 85% for 1 hop, GRAA experiences a gradual decrease, recording a PDR of 74% at 10 hops. This trend underscores potential challenges in GRAA's routing strategies, particularly in scenarios with a higher number of hops. In overview, AARA consistently upholds a high and resilient Packet Delivery Ratio (PDR), demonstrating its efficacy in ensuring dependable communication even in semi-optimal scenarios characterized by an escalating number of hops. While ALSR showcases reasonable efficiency in packet delivery, it encounters difficulties in maintaining PDR as the number of hops increases. GLSR exhibits competitive adaptability to the semi-optimal configuration, maintaining a relatively stable PDR across varying hop counts. On the other hand, GRAA falls behind in PDR, indicating potential opportunities for enhancement in its routing strategies, particularly in scenarios with an elevated number of hops. In conclusion, the nuanced analysis of PDR trends provides valuable insights into the strengths and limitations of routing algorithms in semi-optimal aerial ad-hoc network

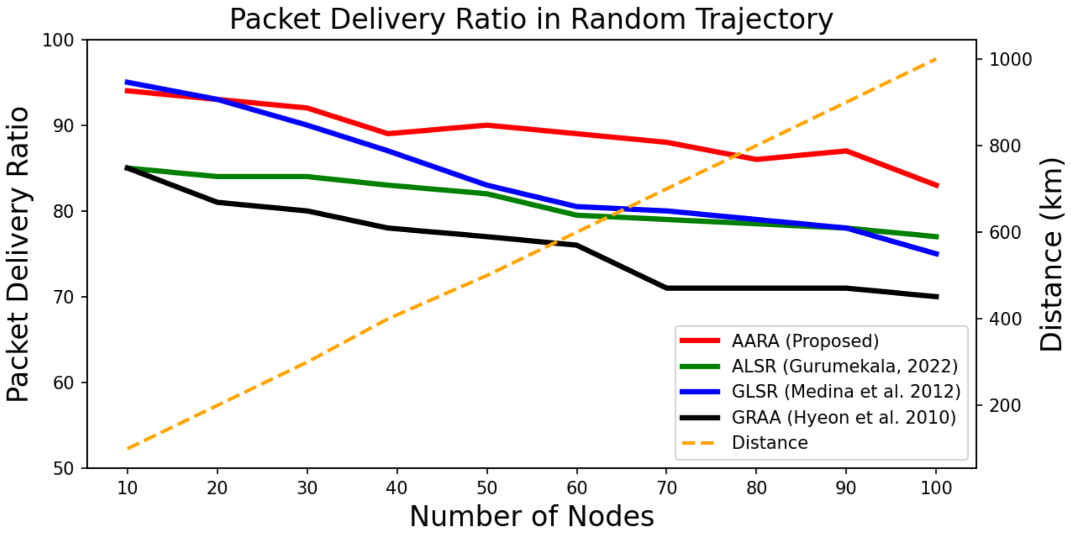


FIGURE 5.8: Packet delivery ratio comparison of aircraft flying on random paths

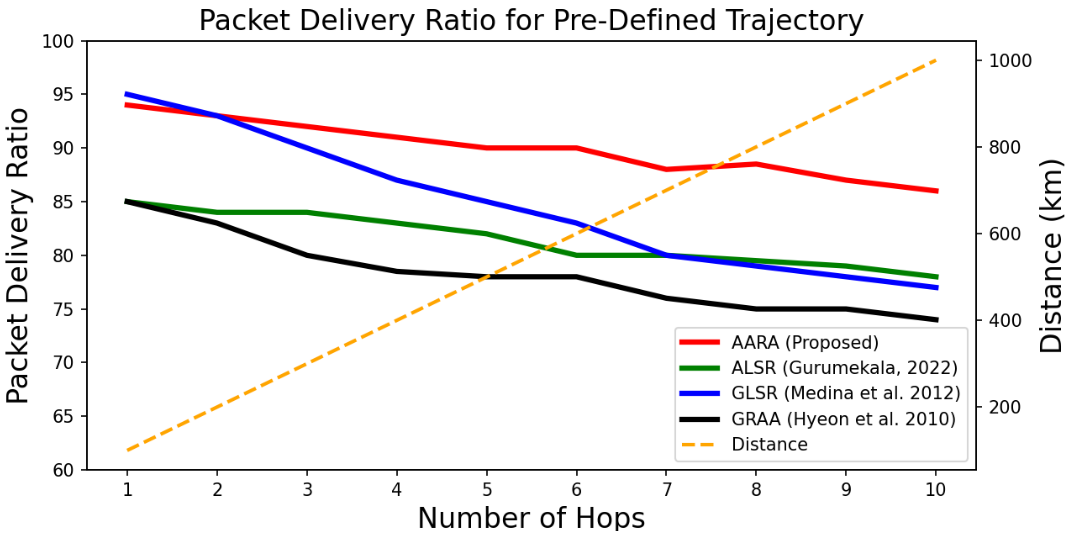


FIGURE 5.9: Packet Delivery Ratio in aircraft flying on a pre-defined path

configurations. AARA emerges as a robust solution, showcasing its reliability and adaptability across varying hop counts. These findings contribute to a comprehensive understanding of routing algorithm performance in scenarios characterized by closely spaced nodes traveling in the same direction.

Chapter 6

Extension of the Proposed Solution for Real-Time Applications

This chapter presents an extension of the proposed solution for real-time applications. An example of unmanned aerial vehicles (UAVs) is taken as a usecase. In Section 6.1, an overview of UAVs is given, whereas Section 6.2 introduces the major applications of UAVs in the sea.

In Section 6.3, the general routing architecture of the Real-time Gradient Cost Establishment (RT-GRACE) algorithm is explored, specifically designed for real-time applications. Moreover, Section 6.4 demonstrates the results and discussion.

6.1 Unmanned Aerial Vehicles (UAVs)

One of the most revolutionary new technologies of the last two decades is unmanned aerial vehicles (UAVs). In recent years, they have gained popularity for a variety of applications due to their adaptability and relatively low cost. Although military applications still dominate the UAV market, the industry is estimated to be worth several billion dollars annually, and the outlook for the industry is promising. The recent impetus for the development of new UAV applications that will lead to increased use is commercial interest, technological advances, the miniaturization of onboard sensors, and new algorithms and software. As UAVs have become more sophisticated, they have replaced the original surveying applications, bringing with them new requirements and therefore new commercial prospects. UAV systems are contributing to the fourth industrial revolution in this field by enabling fast, automatic, and autonomous geospatial data collection. As an example of new and emerging applications, UAVs are being used to monitor building structures and other infrastructure, for precision agriculture, and for indoor search and rescue operations.

6.2 Applications of UAVs in the Sea

In modern times, the use of drones and UAVs is very common. These small flying planes are used for numerous purposes, from agriculture and research to entertainment and surveillance. In the case of marine use, the use of UAVs is diverse in nature. There are certain new use cases for the use of UAVs and drones in the sea. Some of the notable solutions are listed in the following lines:

6.2.1 Rescue and Surveillance

Accidents often occur at sea. A timely rescue can save many lives while preventing financial losses. Currently, maritime police use drones to rescue people from sinking boats or ships and other accidents at sea. Numerous deaths and losses motivate governments to install more drones in the sea.

In the sea, drowning is undoubtedly the most common cause of death. According to the Spanish government, 440 people drowned in 2019 [96]. About half of these incidents occurred on beaches, and more than 80 percent of them occurred without lifeguards. It can be argued that the lack of supervision in these circumstances contributes significantly to drowning. A significantly higher number of drowning accidents occur on beaches that are far from urban areas. Lifeguards are not always present at beaches that are far from urban centers. Therefore, someone is more likely to drown in a remote area where there are no other people available to assist. As a result, rescuers are increasingly using rescue drones to assist. There is a reason why drones are more practical than lifeguards in preventing drowning accidents. For example, a rescue drone can control a larger area from the air because it operates from the ground. The second advantage of drones is their speed, resulting in a quicker response time to an emergency at sea. The third advantage is that rescue drones can be used in conditions that might be too dangerous for human rescuers, preventing further loss of life in emergency situations. Using smart sensors, rescue drones can also collect information that can help with future operations.

6.2.2 Border Security

Illegal immigrants are one of the biggest challenges, especially in the last two decades. War-affected people and people in search of a better future try to enter Europe and other rich countries illegally. Illegal entry into the country is mostly by sea. People smugglers and traffickers use substandard boats that are overloaded. This leads to fatal accidents that are very common and cost hundreds of lives (even in a single incident). Human smuggling is also becoming more common, with children and women in particular being smuggled in from various countries. To prevent illegal immigration and human smuggling, drones and UAVs are being used extensively over the world's oceans.

6.2.3 Pirates and Other Security Threats

Security threats from terrorism and piracy are alarming challenges in today's world. Ships are being robbed, resulting in heavy financial losses and even the loss of life. Pirates kidnap a lot of people, and this kind of thing is happening more often now that communication is getting better. Certain terrorist activities are also possible on or through the sea. Governments spend a considerable amount of money to protect their ships from pirates. For example, in 2017, Japanese defense officials requested 3,200 million Japanese yen for preventive measures against pirates off the coast of Somalia [97].

The sea route from Japan to Europe through the Suez Canal, which must pass through this area, is very important. Japan's Maritime Self-Defense Forces are deploying a fleet to protect their ships. However, it would be much better if merchant ships were able to protect themselves to minimize the need for naval escorts. To achieve this, drones are used to save a large amount of money and other resources. The drones work in several phases to prevent ships from reaching the pirates' vessels. In the first phase, for example, the drones find the pirate ship and warn cargo ships and other merchant ships and boats that are traveling nearby not to approach the pirate ship. Drones can also be used to stop or even hinder ships if they were unable to follow the warning by firing weapons, etc [97].

6.2.4 Maintanance of Ships

There are certain situations when ships have a technical defect. In the past, there have been several incidents where such failures occurred due to a lack of communication. Ships have to wait for a long time (possibly several days) before telling the engineers or other professionals on-site about the problem so that they can send the right equipment to fix it. Moreover, even after reporting such incidents, the ships have to wait for a long time for the equipment and suffer significant financial losses not only for the delivery of the required equipment but also for fuel consumption and other operational costs (especially for cargo ships, also for the delayed arrival to the ship). Traditionally, it costs $15000 [98]. After the revolution in drone technology, UAVs can transport the needed repair equipment much faster and at an incredibly low cost. Delivery of equipment by a drone costs $150 [98]. These unmanned aerial vehicles (UAVs) are not only a cheaper and faster way to deliver equipment than boats, but they also do it in a very safe way.

6.2.5 Medical Assistance

Medical emergencies happen often when people travel, and because ocean trips are so different, they are more likely to cause health problems.

If proper equipment, examination reports, and medications are available, most medical problems can be solved on the ship. Drones are not only used to provide medication, but can also be used to collect samples (blood, urine, etc.) for testing, and the examination reports can be very valuable for diagnosis and decision-making. Also, uncontrolled bleeding is the leading cause of death from preventable injuries, and obtaining blood rapidly has been found to enhance survival. It has been found that the timely provision of blood products (including whole blood, plasma, and platelets) lowers mortality in trauma patients [99]. Based on the above use cases, it is clear that the use of UAVs in shipping is becoming increasingly important. Moreover, in many cases, UAVs require support from the ground station. In such cases, an efficient communication medium is essential to send the data collected by the UAVs to the ground station. Moreover, it is common for such data to be sent on a hop-by-hop basis (in the case of drones operating in a network of drones). On the other hand, it is a well-known fact that the energy and processing power of drones is limited. Therefore, an energy-efficient routing algorithm must be used to achieve better performance and a longer network lifetime. As evident in the above cases, most applications need to respond in real-time, and even a tiny delay can result in major losses (even the loss of life).

Nevertheless, there is still a need for a good routing algorithm for real-time data that has a balance between energy awareness and reliability. Therefore, it is very important to communicate at an optimal level. In this chapter, an energy-efficient real-time routing protocol is proposed that not only fulfills the basic purpose of real-time routing with energy awareness but also strikes an optimal balance between energy efficiency and reliability. The idea of ”gradient cost establishment” is employed, incorporating energy cost, connection cost, and time cost in the form of deadlines. An optimal tradeoff between energy efficiency and reliability is maintained by the algorithm. Performance comparison of the proposed protocol with two well-known real-time routing protocols (ALSR) [94] and Real-Time Power-Aware Routing Protocol for Wireless Sensor Network (RTPAR) [100], shows that the proposed protocol outperforms the existing real-time protocols in terms of energy savings for given values of reliability and throughput.

6.3 General Routing Architecture

This section explains the system model of the proposed routing algorithm in detail. The system model consists of the basic assumptions that underlie the design of the algorithm, the routing model that describes how the algorithm works, and the cost parameters that measure the performance of the algorithm. A key point to remember is that the terms “UAV/drone” and “node” are interchangeable and refer to the same entity.

6.3.1 Assumptions

The efficacy of the proposed routing model hinges on several foundational assumptions, providing a robust framework for its functionality. These assumptions include:

- Location Awareness: Every drone within the network possesses accurate knowledge of its geographical coordinates, ensuring precise spatial awareness.
- Energy Monitoring: Each node is equipped with a mechanism to monitor its remaining energy, effectively represented as a battery status. This empowers nodes to make informed decisions based on their energy constraints.
- Neighborhood Awareness: Each node is cognizant of its neighboring nodes, fostering a comprehensive understanding of the local network topology.
- Distributed Node Placement: Nodes are strategically distributed in a random and dense manner, mitigating the risk of network disruption and promoting efficient communication.
- Uniform Processing Time: For simplicity and streamlined operations, the processing time at intermediate nodes is assumed to be uniform, facilitating consistent handling of data within the network.

These assumptions collectively form the foundational principles upon which the proposed routing model is designed, ensuring its effectiveness in diverse operational scenarios.

6.3.2 Routing Parameters

The proposed methodology relies on key parameters, including Link cost (L_c), Temporal cost (T_C), and path cost (P_C), each playing a pivotal role in shaping the approach.

6.3.2.1 Link Cost ($\mathbf{L}_c$)

The Link Cost L_c of the communication link between any sender node N and any receiver node S can be expressed, mathematically, as:

$$L_{c_n,s} = \frac{P_{t,N}}{P_{r,S}} \tag{6.1}$$

whereas $P_{r,S}$ is the received power of node S and $P_{t,N}$ is the transmission power of node N.

6.3.2.2 Temporal Cost (T_c)

Since the proposed strategy deals with real-time routing, T_c, the Temporal Cost, is very important.

They indicate how much time it takes a packet to travel from a source node to its destination.

In theory, it is the time a packet takes in flight plus the processing time at each intermediate node. Temporal Cost can be expressed mathematically as follows:

$$T_c = \sum_{h=1}^{H} t_p + Ht_0 \tag{6.2}$$

where, H is the total number of hops and t_0 is the processing time at each intermediate node. t_p is the propagation time and can be calculated as

$$t_p = \frac{d}{c} \tag{6.3}$$

here, d is the distance between two nodes and c is the speed of light.
According to Frii's equation, power received at the receiver node can be defined as:

$$P_r = P_0 \left(\frac{d_0}{d}\right)^n \tag{6.4}$$

where P_0 is the power received at the closed-in-reference distance, d_0, while P_0 can be obtained by the following equation:

$$P_0 = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \tag{6.5}$$

where G_t is the gain of the transmitting antenna and G_r is the gain of the receiving antenna, λ is the wavelength of the microwave carrier, and d is the distance between the transmitting and receiving nodes.

6.3.2.3 Energy Cost (E_c)

The energy consumption of a node in a network, expressed as a ratio relative to its initial energy at the time of deployment, is a key parameter that can impact the performance and effectiveness of the network. The energy consumption of a node can be influenced by a variety of factors, such as the amount of data transmitted and received, the distance over which the data is transmitted, and the power of the transmitter and receiver. Understanding and optimizing the energy consumption of nodes in a network can help to improve the efficiency and longevity of the network. Mathematically, it can be written as follows

$$E_c = \frac{\text{Initial Energy}}{\text{Consumed Energy}} \tag{6.6}$$

where, consumed energy $\leq$ initial energy. This implies that the energy of a node increases as its usage of energy grows, and conversely, its E_c decreases.

6.3.2.4 Path Costs

There are two types of Path Cost

(i):Gradient Overall Path Temporal Cost T_c: This parameter is used to calculate the total time required on a path from any UAV to the ground station. If H is the total number of hops on a route from a source to the sink, then the Gradient Overall Path Temporal Cost T_c will be calculated from (6.2).
ii). Gradient Overall Path Resource Cost R_c: This can be calculated by taking the link cost L_c of each link on a route and the Energy Cost E_c of the intermediate nodes, starting from the sink, where the energy cost of the sink is assumed to be zero.

Algorithm 6.1 RT-GRACE Routing Algorithm

```
Input: Source node $N$, sink node $S$, time constraint $T$
Output: Route from $N$ to $S$
$N \leftarrow$ source node
$path \leftarrow \emptyset$
$candidateSet \leftarrow \emptyset$                          ▷ Initialize candidate set
while $N \neq$ sink do
    for each neighbor $S$ of $N$ do
        Calculate $Lc_{N,S} = \frac{Pt_N}{Pr_S}$                  ▷ Link Cost
        Calculate $Ec = \frac{\text{Initial Energy}}{\text{Energy Used}}$        ▷ Energy Cost
        Calculate $Tc = \sum_{h=1}^{H} tph + Ht0$           ▷ Temporal Cost
        Calculate $Rc = Ec + Lc$                        ▷ Resource Cost
        if $Tc < T$ then
            Append $(N, S)$ to $candidateSet$           ▷ Add candidate path
        end if
    end for
    if $candidateSet \neq \emptyset$ then        ▷ Check if there are feasible paths
        Select the neighbor $S$ with minimum $Rc$ from $candidateSet$
        $path \leftarrow path \cup (N, S)$                      ▷ Update path
        $N \leftarrow S$
    else
        Drop the packet and exit the loop
    end if
end while
return $path$                               ▷ Return the selected path =0
```

6.3.3 Proposed Routing Model

In the real-time routing model, a network is initially assumed to consist of a substantial number of nodes distributed randomly and densely packed. This assumption enables the analysis of the network's behavior and performance under various conditions and scenarios. After provisioning, a very important phase called the deployment phase begins as shown in the Algorithm. 6.1. In this phase, two main costs of the network are mainly captured. These are the energy cost E_c for each node and the link costs (L_c) for each connection between any two nodes. To calculate the connection cost L_c between two nodes, the receiving node uses (6.1), using the values of its receiving power and the transmitting node's transmitting power (6.4). The total path or link cost on the link between any sender and the sink is then calculated by adding the energy cost E_c of the nodes on the link together with the link cost L_c of all links. This is done by setting the energy cost of the sink equal to zero and then continuing with the neighbors up to the nodes at the edge of the network. This creates a shell-like cost field like a bowl from the edge nodes to the sink, which is at the lowest point of the bowl. Similarly, the Gradient Overall Path Temporal Cost T_c is traced from the sink to the edge of the gradient bowl (node at the network's edge). At this juncture, there are two distinct costs for each route between a potential sender and the sink: the Gradient Overall Path Temporal Cost and the Gradient Overall Path Resource Cost. Both costs are utilized to determine the optimal route for each packet destined for the sink. For instance, when a packet is present at any sender node with a margin of T time units to reach the sink, it is compared to the list of Gradient Overall Path Temporal Costs for all paths originating from the sender node through its neighbors. The selection is made based on routes with lower Gradient Overall Path Temporal Cost T_c than T and a higher probability of delivering the packet within T time units. From the selected set of routes, the packet is delivered on the route with the lowest gradient Overall Path Resource Cost, R_c. This approach not only satisfies the real-time requirements for packet delivery, but also selects the most appropriate path that uses the optimal resources according to the fading conditions and the remaining energy.

T_c is given at the edges of the nodes. Three outgoing routes start at node Tx and lead to the sink near the sender, with T_c values of 2.9, 5.0, and 6.1, which are obtained by summing all routes from the sink to Tx, as shown in Figure. 6.1. Let T=5.5sec be the amount of time left for the packet to reach the sink. The time cost of all three paths and the two routes with T_c less than T are shown as path1 and path2 in Figure. 6.1. Both routes have a temporal gradient of 2.9 seconds and 5.0 seconds toward the sink, respectively. The final route selection from these two routes would be based on further comparison of the Gradient Overall Path Resource Cost, R_c of both nodes. The route that has the minimum of the two R_c values is selected as the optimized route. This process is repeated at each node on the path until the packet reaches its destination, the sink.

6.4 Results and Discussions

In this section, the performance results of the proposed routing strategy are discussed, along with a comparison with well-known real-time routing systems. It is

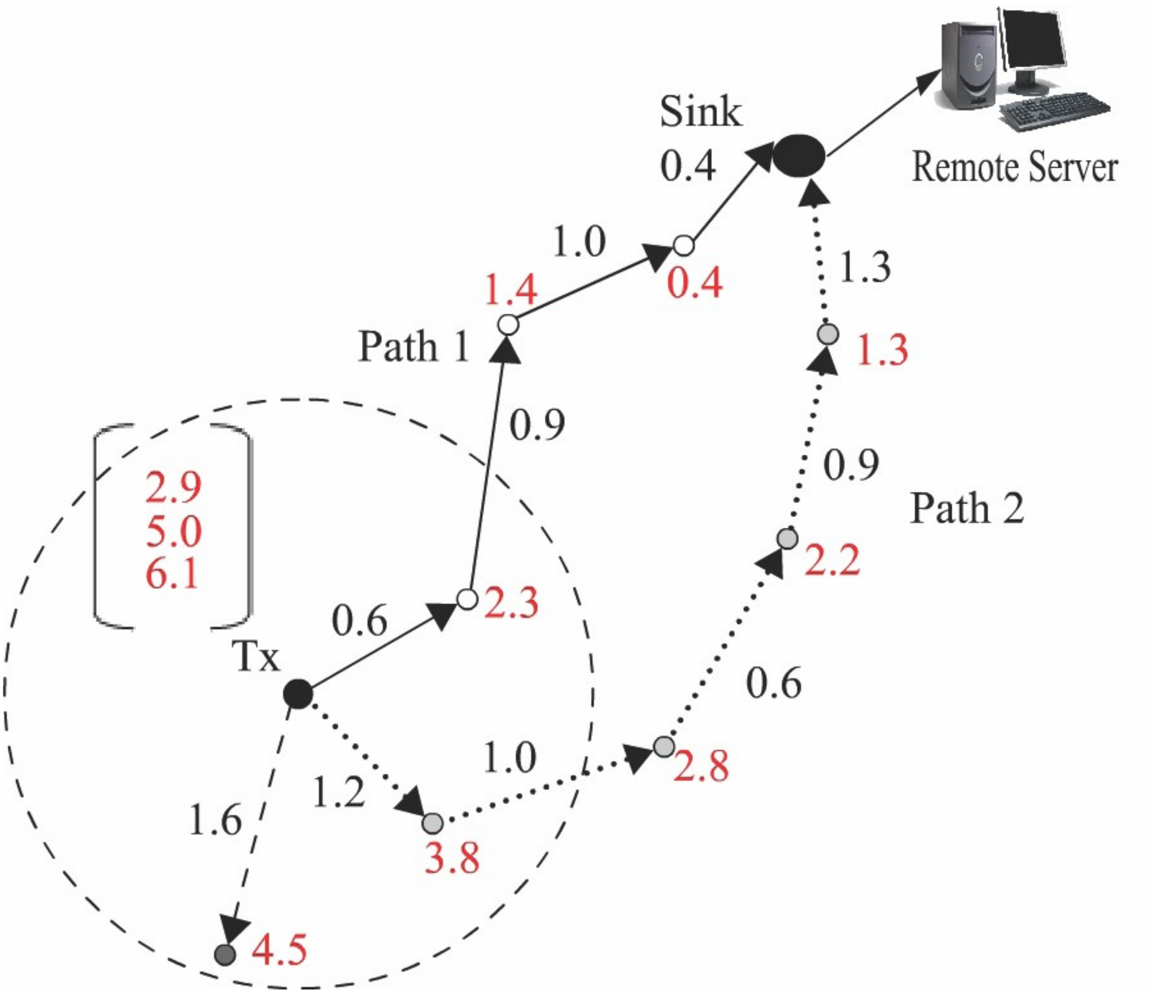


FIGURE 6.1: Temporal Managing of Real-Time data in proposed scheme

worth noting that these results are preliminary. However, the detailed results will be presented and explained in the future work. The simulation was run twenty times in MATLAB with the initial energy of the UAV batteries set to 4000 joules until a significant number of nodes failed and data communication in the network was interrupted. The UAVs are randomly distributed and the connections were based on the radio range of the nodes shown in Table. The performance metrics considered in the simulations are the time cost and network lifetime. The real-time data was generated from eight randomly selected source nodes in the network. Figure. 6.2 shows the temporal cost of the routes originating from ten randomly selected nodes in the network. The different bars in the graph for a single node with a number on the abscissa show the time cost of the paths when it uses its neighbors to reach the sink. For example, almost all of node 5's paths take the most time, while node 9's paths take the least time to reach the sink. Node 6 has the least number of paths, while node 7 has the highest number of paths.

Table 6.1: Simulation Setup Parameters

Parameter	Values
Number of Nodes	10 to 50
Initial Energy	4000J
Simulation Tool	MATLAB® 9.0
Number of Source Nodes	8
Number of Simulation	100 Rounds
Frequency	2.4 GHz
Data Rate	250kbps

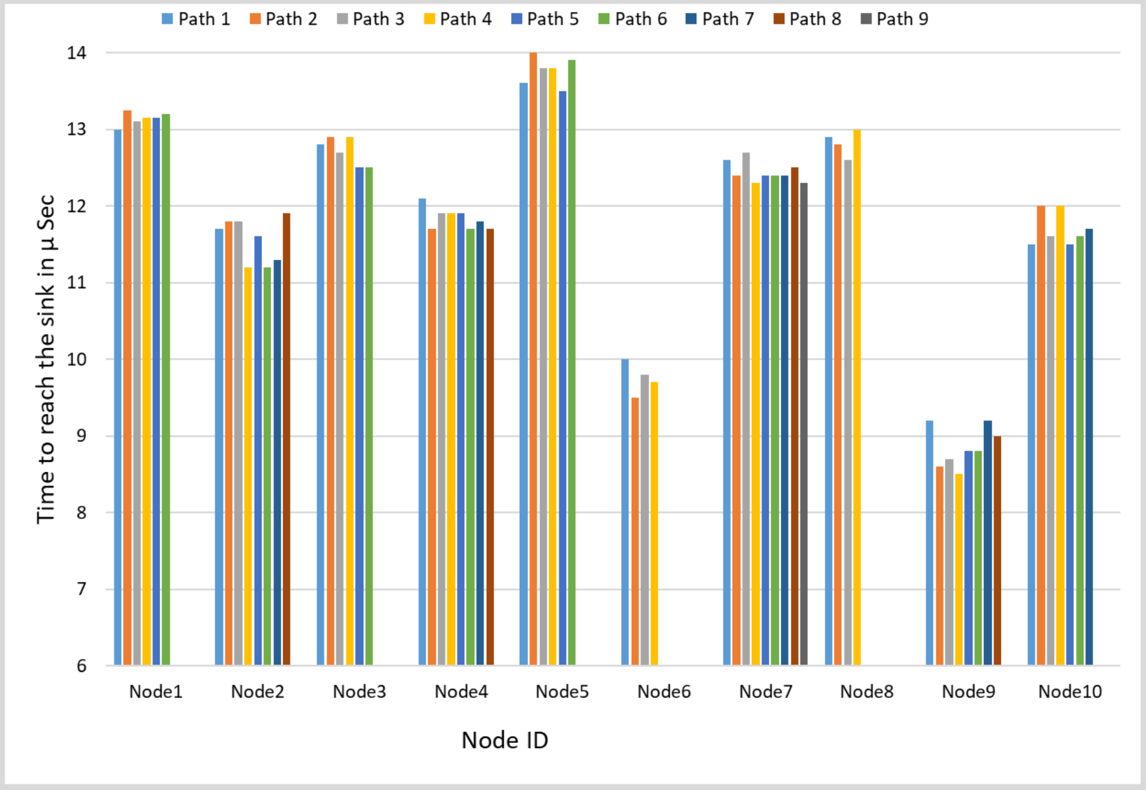
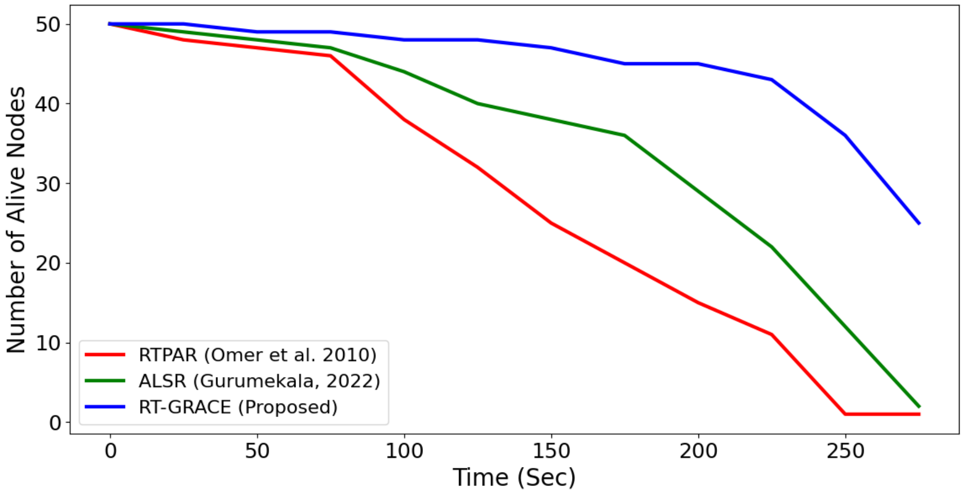


Figure 6.2: An Example Scenario to Explain Temporal Cost

The lifetime of a UAV network is usually considered a very important parameter for the energy efficiency of the network. However, it is important to note that the mechanism of energy efficiency should not exceed the deadlines for the delivery of real-time packets. A longer network lifetime simply means that the network uses its nodes efficiently by selecting longer paths to conserve the energy of the critical



Network Lifetime Comparison of the Proposed RT-GRACE with ALSR [94], RTPAR [100]

nodes, thus extending the overall network lifetime. If this point is not properly embedded in the algorithm, the mechanism of energy efficiency may cause the real-time packets to be sent over longer paths and eventually discarded at intermediate UAVs. The proposed RT-GRACE approach considers both factors in terms of two route costs and applies an energy efficiency mechanism to the routes selected based on the temporal deadlines. For this reason, RT-GRACE outperforms RTPAR [100] and ALSR [94] in terms of network lifetime, and performs better for real-time and energy-aware applications. This is illustrated in Figure. 6.4, that in terms of overall network lifetime, ALSR performs comparably better than RTPAR.

Chapter 7

Conclusion and Future Work

In this thesis, the existing literature on airborne Internet delivery mechanisms has been intensively reviewed, and where necessary, appropriate critical comments have been made. From the literature, it appears that most published articles and deployed solutions use either satellite-based, costly links or ground-based, station-based, ground-to-air (G2A) links to deliver the Internet on aircraft. G2A links work in the same way as mobile land communications, and it is generally thought to be a line-of-sight. On the other hand, satellite links use geostationary (GEO) satellites, which are not only very expensive in terms of their data rate packages but are also prune to huge delays because they are 36,000 km above the Earth's surface. Therefore, satellite links are not the ideal way to provide Internet access to airborne users due to the cost and delay. Providing Internet to aircraft via G2A links, on the other hand, has its own problems. For example, they are only suitable for aircraft flying over land. Therefore, they cannot provide Internet access to passengers flying over the oceans. To overcome the aforementioned problems, a comprehensive solution has been proposed to provide Internet access to passengers on flying aircraft. The first phase of the research presents a detailed solution along with the design for providing Internet access to aircraft flying over the oceans.

Using submarine cables already laid in the oceans, the proposed technology provides Internet backbone service to ships stationed at sea that serve as base stations.

Since the proposed solution does not require expensive and slow satellite links, it is superior to previously proposed solutions. An analysis of the conceptual framework of the proposed solution and a discussion of various research and implementation issues are presented. Unlike traditional cellular land-based cellular systems, the high speed of aircraft results in less available handover time. To analyze these challenges in aircraft handover, a comprehensive geometric analysis was performed. Closed-form mathematical expressions for the handover margin, optimal cell overlap area, and optimal cell radius were derived to satisfy certain predefined parameters. The effects of aircraft motion direction, aircraft velocity, and propagation environment on the handover area were also presented. In the second part, a reliable and scalable routing algorithm has been proposed to extend Internet coverage to aircraft flying beyond the transmission range of the transmission tower mounted on stationary ships. Such an extension of Internet service delivery to aircraft flying far from the main UOFC will enable many important use cases such as cloud computing, live blackox, telemedicine, etc. The proposed work has been positively supported by appropriate models as well as by rigorous simulations. Although the proposed solution does remove the obstacle of satellite links in the path towards the high-speed Internet connectivity to airborne users; however, more research needs to be done to explore and overcome certain issues faced by the airborne users, especially when flying over oceans. The biggest challenge is to overcome the completely different propagation conditions, such as the enormous mobility and range. This makes the implementation of many established terrestrial applications and services very hard for airborne solutions. Therefore, such solutions must be tailored to the fundamental limitations of the airborne communications. The research work presented in this dissertation can be further extended in a number of ways. The following three directions are a few of such extensions:

- **Plan 1:** The proposed research can be extended to its application in drone networks. This will be an interesting research since drones do not fly on a specific trajectory. In addition, the introduction of unmanned aerial vehicle (UAV) technology enables several new use-cases. It also leads to a specific area of the Internet of Things (IoT) known as the Internet of Flying Things. This research is anticipated to provide a foundation for future studies on the Internet of Flying Things.

- **Plan 2:** The results presented in this thesis can be exploited into airborne applications in live black box and live security surveillance. In other words, the proposed strategy for airborne Internet access can also be extended to aircraft security, anti-hijacking and anti-terrorism systems. In history, there are many unfortunate aviation incidents where the black box was not found, especially when the aircraft crashed in the sea. The proposed AARA while providing high speed link will enable a live black box using the pilot's brain-computer interface. The live black box will be beneficial in retrieving the cause of any air accident to prevent further mishaps.

- **Plan 3:** The results presented in this dissertation can also be extended to providing cloud-like resources on GSs or OSs in the close proximity of aerial users. There are several tasks that require large computational and storage resources. Moreover, mobile devices have limited storage and computational capacities. Therefore, such tasks are offloaded to the cloud. Due to the high price of cloud resources, there is a middleware technology called Fog/Edge computing that analyzes and filters the outsourced tasks and sends only those tasks to the cloud that exceed the capacity of the Fog/Edge servers. In the proposed AARA, this can be done by installing Fog or Edge servers with extensive computing and storage resources on the ground stations or the stationary ships.

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