A Quasi Stationary Service Architecture for Network Monitoring and Connectivity Prediction in Aeronautical Ad Hoc Network using Fuzzy C Means Clustering

by

Soumi Ghosh

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the MASc. degree in
Electrical And Computer Engineering

School of Electrical Engineering and Computer Science
Faculty of Engineering
University of Ottawa

Abstract

An Aeronautical Ad Hoc Network (AANET) of airborne elements is a high speed mobile network. The AANET has a 3D topology spread across the airspace. The high ground speed of the airborne elements changes the network topology rapidly. This makes AANET highly dynamic in nature. Upholding the connectivity in the network in such dynamic environment is a challenge. The connectivity in the network is primarily influenced by proximity of airborne elements to each other and their relative velocities. Once an airborne element gets disconnected from the network, it becomes completely oblivious of the network scenario in its neighborhood. In the absence of a monitoring agent in the airspace, a disconnected member of the network largely depends on the ground infrastructure and satellite resources for immediate information regarding its surrounding region. Network monitoring in dynamic environment of AANET is a challenging task, mainly due to the mobility of the airborne elements. We propose an intelligent network monitoring system for AANET. Disconnected members of the network are directed towards region in the airspace with "higher" connectivity and "minimum" traffic under the monitoring system. Our monitoring system depends on a quasi stationary layer of Higher Altitude Platform (HAP) in the airspace. The primary focus of the monitoring system is to mitigate disconnectivity in the AANET. The monitoring of the network is achieved by a periodic monitoring scheme in every HAP. The proposed HAP monitoring system aims at making the AANET more independent of the ground infrastructure and satellite resources. We also reckon Fuzzy C Means (FCM) data clustering as a means to monitor changes in network topology and traffic in the AANET. The FCM clustering is an integral part of our monitoring scheme. Our simulations demonstrate that FCM clustering can efficiently track the network changes in the AANET and identify regions of connectivity in the network.

Acknowledgements

This thesis has been a wonderful journey. I take this opportunity to thank Faculty of Graduate and Postdoctoral Studies, University Of Ottawa for giving me this opportunity.

I am immensely thankful to Dr.Amiya Nayak, my thesis supervisor, for being kind and supportive. His constant guidance during the process has helped me think out of the box. His critical evaluation has always put me on the right tracks towards completion of this thesis. I value this association with him and consider myself lucky to have received his esteemed guidance.

I also convey my sincere gratitude to Dr.Bimol Roy and Dr.Bhabatosh Chanda without whom this journey would not have started in the first place. I give my sincere regards to Sruti di, Sasi Kiran VL Reddy and Rakesh Radhakrishnan for their words of encouragement and well wishes.

I would like to thank my father Mr.Binodranjan Ghosh for supporting me financially through the course, my mother Mrs.Swapna Ghosh and sister Trisha Ghosh for their blessings. I appreciate their patience during my absence in the family.

A special thanks to my room mates Richa and Radhika for being my family away from home. I would also like to acknowledge my friends Iype, Muzammil, Fikirte, Kala and Rituja whose presence has made this journey a memorable experience.

Contents

List of Tables

List of Figures

List of Acronyms

AANET	Aeronautical Ad Hoc Network
ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependence Survillence Broadcast
ALMA	Advanced Link Management Algorithm
ATC	Air Traffic Control
ATN	Aeronautical Telecommnication Network
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V./German Aerospace Center
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Agency
FCM	Fuzzy C Means
FL	Flight Level
FSO	Free Space Optical Link
GSM	Global System for Mobile Communicaitons
HAP	Higher Altitude Platform
ICAO	Internatioanl Civil Aviation Organisation
IETF	Internet Engineering Task Force
MANET	Mobile Ad Hoc Network
NAC	North Atlantic Corridor

NEXTGEN	Next Generation
nmi	Nautical Miles
SATCOM	Satellite Communicaiton
UAV	Unmanned Aerial Vehicle
VANET	Vehicular Ad Networks
VDL	Very High Frequency Data Link
VHF	Very High Frequency

Chapter 1

Introduction

The recent trend of connecting mobile devices has overcome the limitations of working only for hand held devices, such as cellular phones, PDAs, etc. The network of mobile devices requires to be infrastructure independent. Ad Hoc network has flourished as a popular field for research and development in this regard. The Mobile Ad Hoc Network (MANET) now encompasses both vehicular and airborne networks. The AANET, is used for describing an airborne network. The Unmanned Aerial Vehicle (UAV), civil aircrafts, military aircrafts and airborne swarm sensors can form an AANET. The AANET promises to support complete air-to-air communication between airborne vehicles. The prospective utility of AANET has induced considerable amount of research interest in the aviation fraternity. The key focus is on the development of communication infrastructure for supporting AANET communication. Consortiums, for example, Deutsches Zentrum für Luft- und Raumfahrt e.V./German Aerospace Center (DLR) and European Organisation for the Safety of Air Navigation (EUROCONTROL), are actively involved in developing the AANET for present and future challenges. The Internatioanl Civil Aviation Organisation (ICAO), Internet Engineering Task Force (IETF) and Federal Aviation Agency (FAA) are other chief participants involved in such research. Accessing the Internet in “flight”, enhanced situational awareness in mission, sensitive military operations are areas which will be benefited by AANET. The AANET promises to make an aircraft more independent of the infrastructure. Smart Antennae and Automatic Dependent Surveillance Broadcast Automatic Dependence Survillence Broadcast (ADS-B) system are being used for effective air-to-air communication between aircrafts. *Seamless Connectivity* in AANET has been the key focus area in project SANDRA [54]. The utility of AANET for creating better situational awareness and air traffic management has been pointed out in SESAR [12]. Collective efforts are being taken by organizations to extend the utility of AANET at commercial level. Section 1.1 describes the AANET and it's network elements.

1.1 The Aeronautical Ad Hoc Network

Fig 1.1 represents the AANET. The network elements are as follows:

- *Satellite* is used for tracking of airborne vehicles and giving position updates to the vehicles as well as the ground stations.
- *Higher Altitude Platforms (HAPs)* are airborne vehicles in the stratosphere. They are at heights below the satellite but much above the flight levels of the aircrafts.
- *Airborne Nodes* are can be the aircrafts (military or civil) or other airborne sensors. They communicate with the help of air-to-air link and air-to-ground link.
- *The Aeronautical Telecommunication Data Network* (ATN) connects all the ground stations and the core network. It is responsible for Air Traffic Control and Air Traffic Management. The ATN connects the core network to the airborne vehicles.
- *Ground Very High Frequency (VHF) Network* comprises of the radio network on the ground which connects the airborne vehicles to the satellite.
- *Air-to-Air Link* is used for communication between the airborne nodes. These are VHF radio links.

- *Air-to-Ground Link* is used for communication between the airborne vehicles and the ground network.
- *Satellite Link* or the Satellite Communicaiton (SATCOM) link is used in satellite tracking of the airborne vehicles.

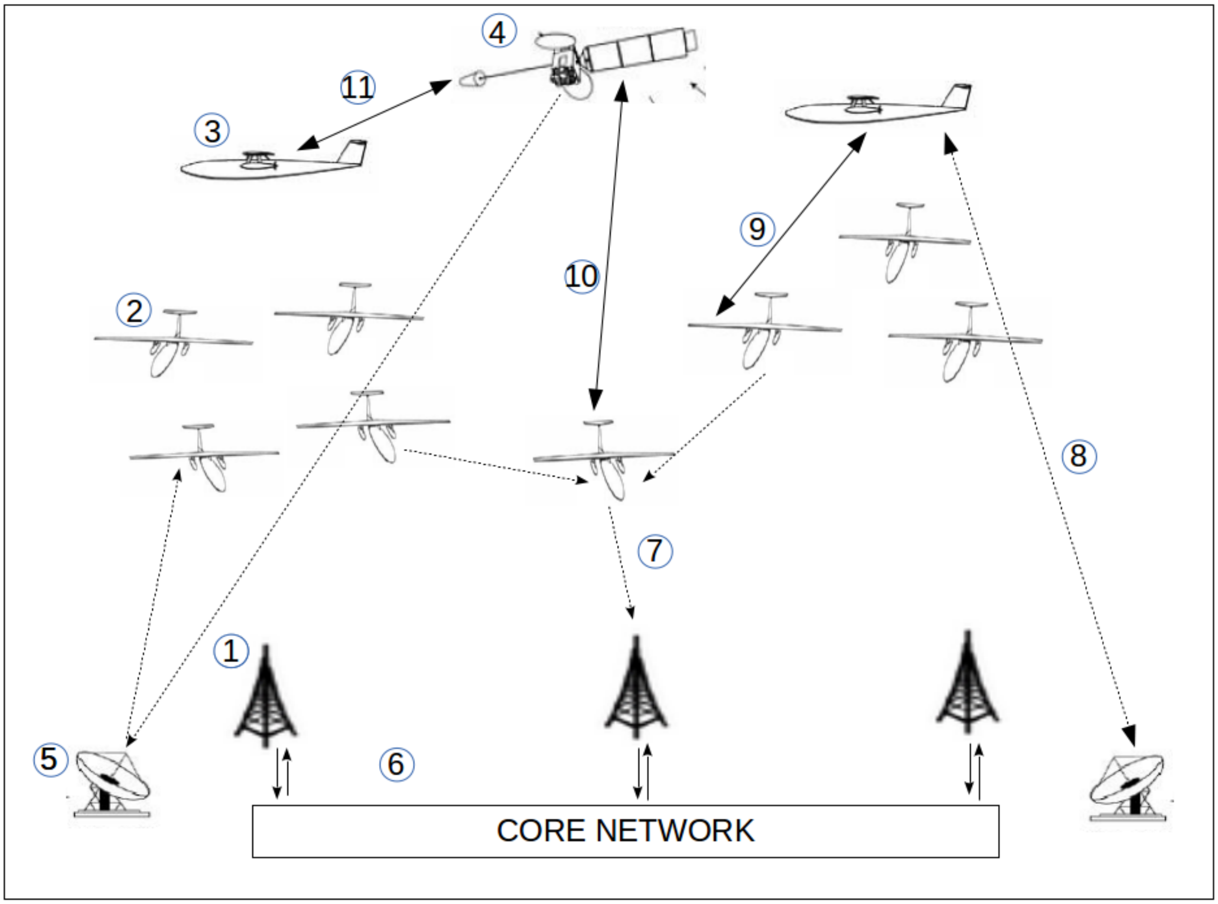

Figure 1.1: The Aeronautical Ad Hoc Network

The network elements in the figure are

1. Ground ATC Network
2. Aircrafts
3. Higher Altitude Platforms
4. Satellite
5. Ground VHF Network
6. Core Data Network
7. Air-to-Ground Link
8. HAP-Ground VHF Network Communication
9. HAP-Aircraft Communication
10. SATCOM link
11. HAP-Satellite Communication
12. Air-to-Air VDL link

1.2 Motivation

Network modeling is a challenging task for network possessing 3-dimensional network topology (e.g., roof top sensors, acoustic water sensors). AANET is a special scenario of 3-dimensional network, where participant members are both static and mobile. AANET involves elements from satellite network and the wired ground network. This makes the system complex and heterogeneous in nature. Therefore, understanding the implications of traditional MANET concepts in the AANET has been a key motivation in this work for studying the current state of art research in the AANET communication.

The AANET is not ad hoc in true sense. This is because it mainly depends on the ground infrastructure and satellite resources. The use of satellite resources increases the cost of communication in the AANET. Realizing an independent network of aircrafts has been another motivating factor behind this research. Currently, applications such as “airborne internet”[55], are largely dependent on the ground infrastructure and the satellite resources. That is, a complete end-to-end path between airborne source and destination cannot be maintained easily. This is due to the absence of a stable service architecture in the airspace. The highly mobile nature of the AANET inhibits formation of a stable service architecture in the airspace. Examining the AANET resources for the possibility of realizing an independent service architecture for the AANET has been another guiding factor for the research.

An intelligent service structure should be capable of tracking the network changes efficiently. For a mobile network, in addition to tracking of network parameters (traffic, end-to-end delay, etc.), maintaining a record of position and velocity of nodes is equally important. Therefore, for establishing end-to-end global reachability to every airborne vehicle, a self sustaining tracking system in the airspace is a must. End-to-end route establishment has been examined by Medina *et. al* [42, 43] and Sakhaee *et. al* [56]. Two distinct network topologies, cluster and mesh, have been proposed for AANET from these work. Both topologies have been presumed to exist separately. However, in a mobile network both cluster and mesh topology of nodes can co-exist. For such scenario in the AANET, the following queries came into focus:

1. Can connectivity in the AANET be consistent with the topology change? Also, how the "isolated" members in the AANET be tracked?.
2. If members in the network get disconnected, can the network heal itself, so that end-to-end path between the members is maintained?
3. Is it possible to deliver knowledge about network changes to the members without overloading them?

The above queries are the major motivating factors in our research. In the following section, we present the primary contributions of this thesis.

1.3 Contribution

In this thesis we studied a typical AANET system. Two major contributions of this research which can improvise communication in AANET are listed as under.

- We propose a service architecture for monitoring the AANET. This is achieved by a "quasi stationary" layer of HAPs in the airspace. The HAPs act as a monitoring agent for the AANET. Our architecture aims at levitating ANNET's dependence on the ground infrastructure and minimize the use of costly satellite resources. A ground cellular network (used for avionic network) can not provide similar service for direct air to air communication in an AANET, without increasing the cost of the system. Moreover, the geographic constraints such as oceanic surfaces and hilly terrains makes it difficult to position network stations (radio towers and controlling center) every where. This means the coverage in AANET is limited and dependent on the ground infrastructure. The proposed service architecture can be sustained in the airspace and provides cellular structure for the AANET in the airspace. This is done by Voronoi space tessellation of the airspace. The monitoring of the network helps in maintaining an overview of the network, which is difficult to achieve because of high network mobility. The network monitoring is a continuous process achieved by periodic registration of the aircrafts. The knowledge of network change is imparted to the aircrafts by a parallel status update process. The chief aim of the monitoring is to sustain connectivity in the network.

- We propose the use of Fuzzy C Means (FCM) Data Clustering Algorithm for tracking network changes in the AANET. The goal is to make every airborne member in the network "aware" regarding changes in the network without overloading them. Network partition is the primary cause of changes in a mobile network. The network may be partitioned in terms of topology and traffic. These are independent events which affect the connectivity of the network, but are hidden from the individual members. We believe that FCM Clustering can be used to track these changes, given any topology scenario in the AANET. Our mathematical analysis shows that FCM clustering can track these independent events. This gives the monitoring agent an accurate perception of the network statistics. Subsequently, when this knowledge is imparted to the members in the network, the effects of network partition are no longer oblivious to them, making them aware of network changes.

1.4 Organization

The organization of the thesis is as follows,

- Chapter 2 presents a survey of the AANET. We have categorized our study of the AANET in terms of network architecture and issues. The present state of art research has been listed. The chapter also identifies the challenges faced in AANET due to its highly dynamic nature.

- Chapter 3 is a discussion on the proposed AANET monitoring scheme. We present the idea of a network monitoring agent in the AANET. We also identify FCM data clustering for translating network statistics into valuable information for the monitoring agent.

- Chapter 4 is an extensive discussion on application of FCM technique for monitoring the AANET. It presents a mathematical analysis on connectivity prediction for the AANET. We also present a routing strategy that can be supported by the HAP service architecture in the airspace.

- Chapter 5 holds the concluding comments of our work. The future possible extensions of the research has been put forward.

Chapter 2

Background and Related Work

2.1 Aeronautical Ad Hoc Network: Current State of Art

An AANET, as seen in Fig. 1.1 (Ch.1) comprises of

a) The Aeronautical Telecommnication Network (ATN),

b) The ground VHF network,

c) The satellite and Higher Altitude Platforms, and

d) The aircrafts or other airborne vehicles.

The ATN and the ground VHF network together form the ground infrastructure. An airborne vehicle is connected to the ground infrastructure via air-to-ground links. These are mainly Very High Frequency Data Link (VDL) (band 117.975 137 MHz). The ATN and the VHF ground network are analogous to the cellular Global System for Mobile Communicaitons (GSM) infrastructure, used by the cell phones and other mobile devices. The data transfer in the ATN is based upon the ATN/OSI reference model. The ATN/OSI data transfer model closely follows the OSI data reference model. The one-to-one communication between airborne vehicles is established using the air-to-air links. These are radio links. The onboard antenna on the airborne vehicles are used to set up these radio links. The antenna characteristics influence the range of communication between two airborne vehicles. The channel allocation and the bandwidth available for transferring data depend on the carrier access technologies [66]. Two separate data transfer events occur in the AANET: the data transfer between airborne vehicle and ground network and the data transfer between the airborne vehicles. The data transfer between two airborne vehicles in the AANET can occur simultaneously with ground data transfer (flight tracking and reporting system). The ATN also forms the core network of the AANET. The core network connects the AANET to the Internet and the ground data network.

The ICAO sets the protocols and standards for the avionic network in the international airspace. The avionic network chiefly comprises of the civil and military aircrafts. Every airborne vehicle (civil or military) has a 24 bit identifier address under ICAO specifications. These vehicles are tracked using the satellites and ground radio tracking system. Every aircraft is equipped with an Aircraft Communications Addressing and Reporting System (ACARS). It is a digital data link system, for generating and transmitting tracking updates to the ground station. The tracking is, therefore, regulated by the ACARS. The tracking update messages issued from an aircraft can be an Air Traffic Control (ATC) message, an Aeronautical Operational Control message or an Airline Administrative Control. These message which are transmitted to the ground subnetworks by the aircrafts using VDL. The ground VHF network and the satellite communication system, facilitate the real-time communication between the aircraft and the ground end system. It is evident that, an aircraft depends on the ground infrastructure and satellite resources for situational awareness. However, this dependence is restricted in areas where ground VHF network is inaccessible due to geographical limitations (e.g., oceanic surfaces). Hence, the AANET plays an important role in such areas. In these areas, the aircrafts can remain connected to the ground stations using the resources of neighboring aircrafts. Direct air-to-air communication between two aircrafts is primary requirement for the AANET. For direct air-to-air communication between aircrafts, the VDL modes 1, 2, 3 and 4 [11] have been examined. The VDL mode 4 has been suggested for air-to-air communication between two aircrafts. Section 2.2 is a brief insight into AANET.

2.2 Background

The airborne network is a MANET in 3-dimensional space. The network topology is governed by the velocity of each node, the relative velocity between the nodes, and the separation between them. The network can be visualized as three layer structure as shown in Fig. 2.1. Layer one is formed by the ATN and the VHF network on the ground.

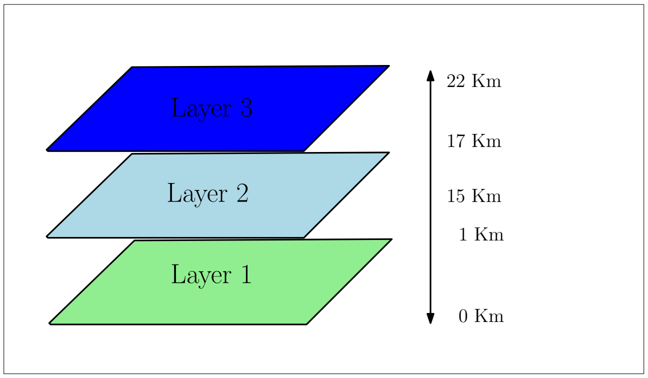

Figure 2.1: Layer Diagram: Aeronautical Ad Hoc Network

Layer two is formed by the airborne vehicles, flying at different Flight Level (FL). Layer three is constituted by the Higher Altitude Platforms and the satellites. The network traffic can be directed within a layer or in between the layers. Any such traffic flow between the nodes is a part of AANET communication.

Significant research initiatives are being taken to develop the current avionic communication infrastructure, for supporting AANET. ATENAA [2][22] project, commissioned by EUROCONTROL, studied the feasibility of AANET in civil aviation. It outlined the changes required in the current infrastructure for supporting ad hoc communication between two aircrafts. The use of Free Space Optical Link (FSO) for air-to-air communication between the aircrafts suggested, along with inflight FSO links for communication within the aircraft. The NEWSKY [60] also investigated the AANET for civilian aircrafts. It listed the properties an aircraft should have for being a part of the AANET. An IP based protocol stack for mobile communication between airborne nodes was built. These initiatives project that, *any node in the avionic network, static or mobile, with capabilities of air to air, or, air to ground communication, and an intelligent system to make routing and control decision can be a participant of the AANET.* The UAV and airborne swarm sensors are other examples of airborne vehicles which can form an AANET. Section 2.2.1 lists the applications of AANET present in the following literature [6][12][22][50][51][55][59][62][71].

2.2.1 Applications

a) **The Airborne Internet** is the most commercial application of interest of the AANET. Currently the Internet services are restricted to the use of satellite ISP and the ground cellular network. The access to the Internet in both intercontinental and transcontinental flights can be improved through air-to-air communication between aircrafts. Flight routes over oceanic surfaces and other inaccessible regions can be given access to the Internet through AANET.

b) **Free Flight and 4D Trajectory Management** aims at revolutionizing the air traffic management system in the airspace and the airports. An en-route flight capable of making changes in its flight plan without depending on the ATC system is said to be on a free flight. This is popularly termed as the 4D trajectory management. NEXTGEN discusses the evolution of 4D trajectory management in aircrafts, aims at giving distributed control to each aircraft. Hence, every aircraft can make independent decisions en-route and can relay this data to another neighbor aircraft through the AANET. This would make the system more reliable.

c) **Military Aviation** including manned and unmanned military vehicles can form aeronautical ad hoc networks. Such networks may be utilized for the purpose of surveillance while coordinating a large number of aircrafts at the same time. As military vehicles fly at much higher velocities than commercial aircrafts, the air-to-air communication between such nodes is comparatively short lived. This makes coordinated surveillance a challenging task. A proper ad hoc network can help in achieving longer duration of exchanges between military vehicles. This opens the possibilities of more efficiently coordinated military flight operations.

d) **Flight Health Management** is yet another area which is expected to benefit from the AANET. Recording and maintanence of flight data can be improvised with distributed data collection in AANET, when ground communication is limited or not available.

e) **Higher Altitude platform broadband network** can be realized through AANET. The HAPs provide multi-hop communication in the AANET. Use of HAPs instead of satellite services, will reduce the cost of the system.

The AANET is highly dynamic. The heterogeneous access technologies involved in the communication lead to inadequacy in the network. The absence of proper network layer, physical, and link layer protocols for ad hoc communication decreases the throughput of the network. Section 2.2.2 presents our study on the major issues of connectivity and link establishment in the AANET.

2.2.2 Issues in AANET

a) **Connectivity** Given two aircrafts, the Line of Sight communication range between them is limited by the earth's curvature and their height above earth's surface. It has been reported that, the maximum range of air-to-ground link can go up to 200 Nautical Miles (nmi). Similarly the maximum range of air to air link can go up to 400nmi for two aircrafts. Though the range of communication is large, the connectivity in the AANET is mainly affected by the high velocity of the aircrafts. An aircraft's velocity can be up to to 1500m/s, or approximately 3.5 in Mach Scale. The relative velocities between two approaching aircraft can be in the order of Mach 7. In such dynamic scenario, the time for communication between two nodes is very less.

The probability of forming a network in a given airspace increases with the density of the nodes in the area [18]. However, for a given node density, the probability of link establishment between two aircrafts depends on their separation from each other [47]. It also depends on their relative velocities. Theoretically, every node 'N' can form links with (N-1) nodes in the network. However, due to constraints of the dynamic topology and signal loss, the number of active links a node can establish is restricted. Thus, if an AANET is formed in an airspace, there is always a probability, that some aircrafts remain 'isolated' from the network [36]. Hence, the necessary and sufficient range of transmission [74] is an important criteria which ensures the connectivity in the entire AANET. Thus, some nodes have higher probability of being connected to the network. This means the coverage of the network depends on the node degree [67].

b) **Interference and Link Layer Scheduling** For given active links formed by a node in the network, at a given instance it can either receive or transmit signals. Improper scheduling of the transmission can lead to interference and collision. The interference estimation in network (mobile and static) is separately studied in [9] and [21]. In [8], the wireless access for the aeronautical ad hoc communication is studied for both, communication between aircrafts and for satellite links. Various Wireless access technologies such as the Wi-Max and Wifi have been considered for communication between the nodes. The use of IEEE 802.11 is not ideal for AANET due to range limitation. At the same time, other wireless access schemes such as Wi-Max has limited use due to cost limitations.

2.3 Related Work

Section 2.3.1 is a discussion on network architecture for AANET.

2.3.1 Network Architecture

The bulk of research initiative is directed towards developing a standard network architecture for the AANET. A network of UAV or an airborne network of swarm sensors can be simply represented by peer-to-peer links between the nodes. These networks are relatively simple to perceive than AANET of military or civil aircrafts. In the physical layer the communication takes place through directional antennae or radio links. The message exchanges are done through simple beacon messages and acknowledgments. The ad hoc communication in the mobile avionic network, however, requires modification to the existing resources for achieving smooth data transfer between the nodes. Designs [30] have been proposed and patented to accomplish air-to-air communication between the aircrafts. To provide provision for mobility of the aircrafts, the data transfer model for the AANET is being merged with the IPv6 and MIPv6 routing for global reachability. The first occurrence of protocol stacks for the avionic AANET in the literature can be seen in the ATENNA project. ATENNA characterized the data transfer layer of AANET with respect to the ATN/OSI model and provided an Advanced Link Management Algorithm (ALMA) for managing different technologies at the link layer.

In general, an aircraft is a mobile router consisting of mobile network nodes (MNN). The mobile network nodes are devices such as PDAs, laptops etc. The ground stations are termed as access routers, or Internet gateways. Every mobile router has a home agent. When a router moves away from its home agent, it needs to configure itself with a local home agent. The MNN takes the address of the mobile router. NEMO presents a protocol stack for such an architecture of AANET. The NEMO has also been scrutinized and extended for route optimization in [4][20].

Medina *et al.* make a comprehensive study of protocol stack architecture suitable for Internet connectivity in [43]. Three network architectures are discussed viz. nested NEMO, MANET centric IP architecture, and MANET centric sub IP architecture. A unique IP address is obtained by converging it with 24-bit identifier address of the aircraft. The authors conclude that a MANET centric IP architecture is most suitable for AANET, since MANET routing at the network and transport layer well accommodates the mobility of nodes. An alternative network architecture is *Cross Layer Network Architecture*. A cross layer conversion takes place between IP and the MANET centric protocol. Hence, while mobile routers hold IP addresses, these address are converted to MANET suited address before being included in the routing packets. This reduces the overhead in the routing packet as the converted node ID is lesser in length than original IP address. The ANTP suite, which comprises of the aeroRP, aeroNP and aeroTP employs a cross layer protocol architecture based on the iNET framework. In the network and transport layer, aeroNP and aeroTP make the necessary changes regarding node IDs. Other works which have suggested similar kind of cross layer architecture can be seen in [62].

Section 2.3.2 gives a brief discussion on the mobility modeling in AANET.

2.3.2 Node Mobility

Mobility of the nodes is one of the significant properties that regulates the communication between them. The AANET is 3D and is highly dynamic in nature. Thus, realistic modeling of the network is necessary for accurate analysis of the AANET in a simulation environment. Several mobility models [15][31] are known for modeling of wireless mobile ad hoc networks. For a 2D network topology, the random way point or random walk mobility model can be used to represent a 'memoryless' system of nodes which means that a node's current position and velocity are not dependent on it's previous position and velocity values. The 2D Gauss-Markov mobility model, however, allows the system of nodes to have a 'memory'. This means, with a tunable parameter, α, one can regulate the nodes' velocity and position vectors' dependence on their previous value. A comparative study of Random Way Point Model and Gauss-Markov modeling [3], shows that Gauss-Markov modeling of the network leads to better performance.

Although a 2D Gauss-Markov model improves the network performance for MANET, it does not represent the 3D topology of the AANET. In [13] the 2D Gauss-Markov mobility model is extended to 3D. This accounts for the multi-tier network which can represent the ground stations and the airborne vehicles together in the topology. The model has three parameters. The tunable parameter α, the mean direction parameter, and the "pitch" for calculating position of the vehicle above the horizon. Even though 3D Gauss-Markov model gives a 3D perspective, it does not account for the acceleration of the aircraft. [38] gives a Semi Gauss-Markov process which not only considers the acceleration of aircrafts but also considers the angle of flight and wings of the vehicle for mobility modeling. A better approach to model the AANET is using the Smooth Turn Mobility Model [68][72], which correlates the acceleration of an aircraft with its spatial position to predict the mobility of the aircrafts. Section 2.3.3 gives a brief discussion on the cluster formation in AANET.

2.3.3 Clustering in AANET

For better resource management in any network, one looks at possible options to pool resources. This ensures better cost effectiveness in terms of network parameters, such as throughput and end-to-end delay. While forming clusters of aircrafts, the mobility plays a very important role. Thus, the clustering algorithms such as those proposed in [39][73] for MANET systems may not be applicable to AANET. The distributed clustering algorithm, MOBIC [5], utilizes power of signal reception as a means for cluster head selection and used the mobility information of the nodes. However, in AANET, the strength of received signal is largely affected by relative velocity of nodes and atmospheric interference; hence, the parameters for cluster formation should not depend entirely on signal strength.

The concept of clustering in commercial aircrafts was first put forward by Sakhee *et. al* in [55] and also discussed in [56][58]. The authors proposed the idea of clustering aircrafts over continental masses for routing Internet data within AANET, depending upon the source of origin of the aircrafts. The concept of 'Doppler value' was introduced. The Doppler value accounts for the Doppler shift of packets received by nodes due to their high relative velocities. The authors proposed *initial* and *progressive* two-stage clustering schemes *dynamic link duration clustering-DLDC* and *dynamic Doppler velocity clustering- DDLV*. The metrics *Doppler Value- DV* and *Inverse of Link Expiration Time-LET* are used respectively in the algorithms for making clustering decisions. The link expiration time helps in predicting the link stability between two nodes and hence is used as a metric for creating stable clusters. Using DLDC and DDLV, authors claim to achieve stable clusters for longer duration of time involving fewer cluster switches. The clustering process starts at every 'NULL' node. A node which wants to be a part of the cluster broadcasts a beacon message in the neighborhood. Simultaneously, every node in the neighborhood (which are at one hop distance) receiving beacon messages, calculates the Doppler Value Sum (DVS), by adding the Doppler values of all the beacon packets received. The DVS is then broadcasted along with the node Id. If a node receives DVS from its one hop neighbors, it compares it, with its own DVS value. If the node is at lower DVS value, it broadcasts a *CLUSTER CLAIM* to all its one hop neighbors. Null (unknown) nodes receiving cluster claim messages can decide to be a part of the cluster and respond by *JOIN REQUEST* message. A null node may receive cluster claims from more than one node, in such scenario it can choose to become a gateway. Thus, through minimum DVS value, the most relatively stable node is elected as cluster head. Since it is relatively stable than all its one hop neighbors, the cluster is maintained for a longer duration of time.

The idea of Doppler Value is also used in [24] for deriving a joint cost metric. The joint cost metric helps in estimating the least congested node. A hybrid routing scheme for inter-cluster and intra-cluster routing is presented. The routing scheme minimizes the joint cost metric to select the most suitable relay node for forwarding packets. Another novel way of clustering in AANET has been presented in [46]. K means clustering is used for clustering in a 'mixed network' of airborne ad hoc nodes and stationary ground nodes to optimize gateway selection in the heterogeneous network and hence realize a better spectrum efficiency. Although the above clustering techniques achieve stable clustering and routing, the proposed clustering algorithms, however, do not address the case of *node migration*. It is evident that the clusters as a whole are mobile. In such a scenario, when a node moves out of one cluster, there is a certain amount of delay before it is accepted in another cluster. Also, if a node in a route between source and destination stops responding, the network takes time to set up the alternate path due to sudden change in topology. In case of merging of two clusters, on going packet transmissions may be affected. In order to avoid these conditions, every node should be able to identify itself with network changes at the global level creating network awareness. The problem of orphan nodes or isolated nodes in the network is also not completely resolved. Section 2.4 gives a brief discussion on routing and congestion in AANET which influence the network traffic scenario.

2.4 Network Traffic

The data traffic in the AANET may enter and leave the network from any of the three layers. The data is always directed between a source-destination pair. The source and destination nodes can be spread across the three layers. When an aircraft fails to reach the ground station, it tries to route its data through neighboring aircrafts. Thus, usually the ground layer consists of the end node. However, an airborne node can also be an end node and is the focus of present research. Considering all the facts mentioned, it is understood that essentially the traffic in the AANET flows in three ways as listed below.

a) The up-link and the down-link traffic from the airborne vehicles to the ATN data network on the ground.

b) The data relaying in the second layer, from one aircraft to other.

c) The data traffic between the satellite, HAPs, and the ground VHF network.

2.4.1 Routing

Topology of the network and the instantaneous position of the nodes primarily govern all the routing tasks in the AANET. The next major factor to be considered is the mobility of the nodes. There are two ways of analyzing the mobility of nodes, firstly their ground velocities and secondly their relative velocities with respect to each other. These factors regulate the two main phases of 'route discovery' and 'route maintenance' in AANET routing. The existing routing protocols in the literature aim towards minimizing end-to-end delay between nodes and maximizing the throughput by improving the packet delivery ratio. These network parameters are mainly affected by:

a. *Overhead of control packets used for routing purposes:* The overhead involved in the control packets should be minimum. The inclusion of mobility and position vectors of nodes, increases the packet overhead. An increased packet overhead implies larger processing time in the nodes which directly affects the speed of queries and acknowledgments of packet while routing data.

b. *Node density in the airspace:* A highly populated airspace in a neighborhood of a node increases the probability of connectivity in AANET. However, a densely populated neighborhood may lead to congestion in the network and subsequently packet drops. A sparse network leads to several isolated or non-reachable nodes and hence decreases the connectivity in AANET.

c. *Distance between two nodes:* Beyond the minimum LOS range of communication between two nodes (moving towards each other or away from each other), the air-to-air link is weak and may get disconnected. On the other hand, when nodes move towards each other, the time of communication between nodes keeps on decreasing. Thus, ideal transfer of data takes place at optimum LOS distance between two aircrafts flying at particular flight levels.

d. *Node mobility and Doppler shift of packets:* The relative velocity of two communicating aircrafts leads to Doppler shift of the packets received at the destination. This Doppler shift can be calculated by measuring the difference in frequency of the received signal to that of the transmitted one. The Doppler shift of packets is important in perceiving the relative stability of node as a candidate for relaying signals.

e. *Queuing delays:* The delay induced in transmission of packets to the next node depends on the buffering speed of queues at every node. The more time a packet spends in a queue, the end-to-end delay increases accordingly. Thus, efficient scheduling algorithms in the queue is another area of focus for improving routing in AANET.

f. *Neighbor discovery process:* Either a node can take topology updates from ground/satellite infrastructure or a node can discover its neighbors by listening to ADS-B messages.

The ADS-B is a relatively new technology. Every aircraft with ADS-B equipment is expected to broadcast an ADS-B message periodically. This ADS-B message can be received by all aircrafts in the listening range. An ADS-B message contains important data vectors of position and velocity of aircraft. It also contains the traffic information in the form of Traffic Information (TIS-B) and Flight status Information (FIS-B). ADS-B helps in live tracking of aircrafts and reduces the dependence on the ground infrastructure. Fig. 2.2 shows live ADS-B tracking of aircrafts across the North Atlantic Corridor.

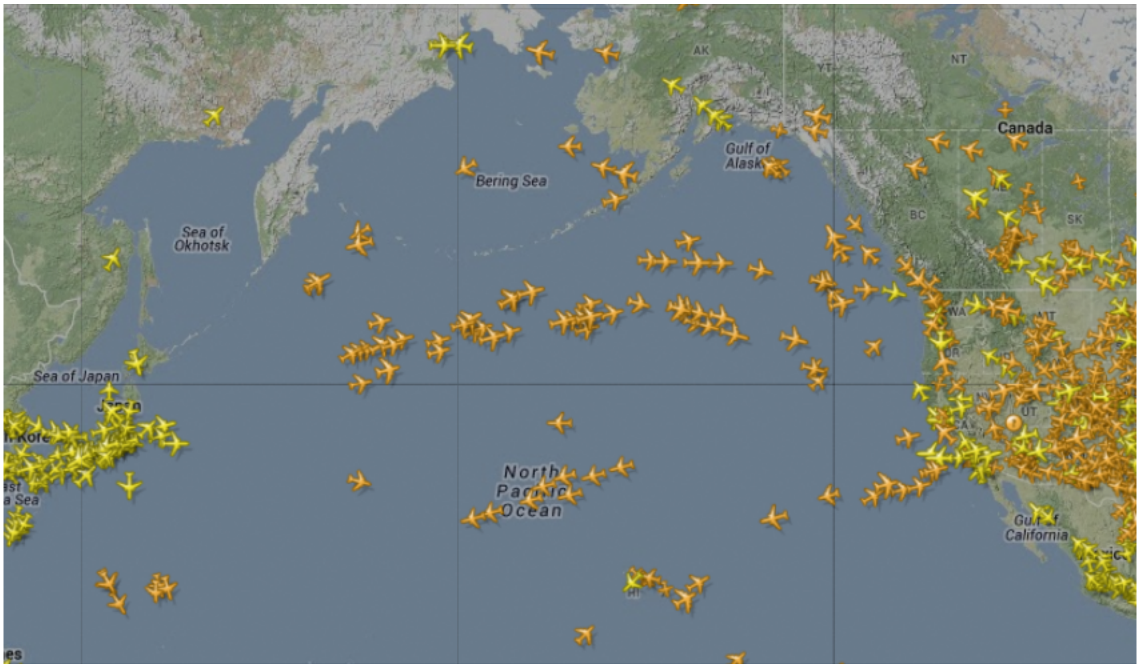

Figure 2.2: Live ADS-B Tracking of Aircraft [1]

Depending upon the neighbor discovery process and the optimum choice of relay nodes for forwarding packets, the topological and position based routing schemes can be categorized as follows:

Reactive Routing techniques are those where a forwarding node is not required to save routes to all possible destinations all the time. Instead, routes are queried and saved *on demand* as and when a node needs to forward a packet. Reactive forwarding is suitable for AANET. This is because, at a global level it is difficult to maintain end-to-end routes for all possible destinations, specially when the nodes are on the move. MUDOR [58] uses the Doppler value metric as a decision value to select best possible node among the one hop neighbors for forwarding the packets and to predict link stability.

Hybrid Routing is usually combination of two or more routing schemes to achieve optimal results. ARPAM [29] is based on such concept. It is a reactive scheme, incorporating AODV [14] and TBRPF [49] protocol for route discovery and maintenance. It finds the shortest path between source and destination and maintains the complete end-to-end path.

Geographic Position-Based Routing utilizes the position information of the nodes. The position updates of the aircrafts can be obtained from satellite or the ADS-B system. These position information about the node is included in the beacon messages, so that nodes receiving the messages can make routing decision. With position information the nodes can either forward data to nodes reactively or in greedily. In greedy forwarding schemes, packets are forwarded to the node 'closest' to the destination. Some position-based routing used in MANET are DREAM, LAR and GPSR [34] which use the location information of the nodes. The aeroRP[52] uses the position information of the nodes to estimate the *Time to Intercept-TTI.* TTI is used as a decision metric to estimate the proximity of the relay nodes and also the time of link connectivity. GLSR [44] is also a position-based routing scheme. It employs greedy forwarding. It estimates the speed of advance of a node towards the destination and greedily forwards the packet to the node moving closer to the destination always by assigning priority to active links. Position-based Routing schemes using ADS-B system, depend upon ADS-B messages to find position updates of the node. Seo *et al.* use the ADS-B system for neighbor discovery phase and propose a routing scheme [61] which integrates the GPSR routing with ADS-B. Mahmoud *et al.* enhance routing a ADS-B based routing in [7]. A-GR [70] is another routing scheme which uses ADS-B messages to calculate an Instantaneous Flight Time(IFT). The A-GR shows better performance than GPSR [76] and GRAA [28].

Cluster-Based Routing are used for inter-cluster and intra-cluster routing of packets. Essentially, the routing scheme can forward packets reactively/greedily. The main aim is route maintenance and creating backup paths in the event of re-clustering. Sakhee *et al.* use the DV in multi-path Doppler routing, to achieve stable clustering in highly mobile ‘pseudo linear networks’. CBHR [24] is a hybrid derivation from MUDOR. It uses a joint cost metric based upon DV, delay and node degree, for establishing routes in cluster and setting up backup paths. CBHR shows a better performance than MUDOR, due to the fact that it considers congestion in the node and also density of the network, for taking clustering decisions.

2.4.2 Congestion

The delay in the network affects the throughput of the network. Distant source-pair nodes and link disconnectivity increase the end-to-end delay for packets. The interference of packets transmitted can lead to collision and congestion or traffic is another factor which introduces delay in the network. Congestion can occur due to heavy traffic or sudden burst of traffic in the nodes. In the multi-tier network, the ground nodes or gateways deal with maximum amount of down-link traffic, as traffic from the airborne nodes is directed towards the ground layer. In the airborne layer, cluster head and gateways between clusters are expected to handle maximum amount of traffic. A relay node in a source-destination route may get congested if, many packets are waiting in its buffer for transmission. Another possible cause of delay in the network might be due to longer route taken by a packet to reach destination. This can happen due to improper forwarding. In such cases, packets are piggy-backed in the queue, and eventually a long waiting time leads to lesser packet delivery ratio and higher end-to-end delay. Concisely, the delay and congestion in the network can be managed through ***proper gateway selection mechanism***, ***proper selection of relay nodes***, ***good queue management in nodes*** and ***proper link layer scheduling***.

The congestion in AANET can be understood from the example of Airborne Internet [55][57]. The Internet was first made commercially available to the passengers by Connexion Boeing through the use satellite broadband service [32] [35][53]. Eventually, it was pulled off from the commercial use. Other service providers are the GoGo in flight Internet and Aircell using Inmarsat satellite links. For providing Internet service to the aircraft, which are far away from an Internet gateway(IGW), a mesh network is proposed by Medina *et al.* [42] [43]. To deal with the traffic load at every gateway, a two-step delay based gateway selection mechanism is proposed [25]. The mobile aircrafts select the terrestrial gateways through proactive mechanism. In the first stage, the path delay for all reachable gateways are noted by an aircraft, in the second stage a gateway with minimum path delay than the current IGW of the aircraft is selected. The traffic is then split in between the two gateways. The gateway section mechanism has been further improvised by use of genetic algorithm in [26] and through joint scheduling and routing [27] for minimizing end-to-end delay.

The link layer scheduling is important to avoid collision of packets. CSMA is not suitable for avionic networks. The most popular choice for preventing MAC contention is by the use of TDMA scheduling. Under TDMA scheduling, every aircraft is assigned a particular number of time slots. An aircraft can transmit and receive packets in its active time slots. In this way, collision between packets in avoided. The iNET framework is based on the TDMA scheduling. Also, the ADS-B messages are transmitted using an UAT frame, which follows basic TDMA link scheduling. Spatial reuse TDMA or STDMA is another candidate for the purpose. DMDR[23] is a delay-aware routing mechanism which uses link layer scheduling for queue management in the aircrafts. A decision metric based on queuing delay is calculated. The queuing delay of the packets is derived using Little's formula. The scheduling algorithm in DMDR uses TDMA based UAT frames. I-TDMA [37] is an interference-based distributed TDMA scheduling technique proposed for the aeronautical relay network. It uses link priority to decide on packet scheduling during active time slots. Matolak *et al.* present a comparison [75] of time and frequency techniques for duplexing schemes, multiple access schemes, and multiplexing schemes for the relay network in the avionic environment. By examining the bit error rate performance of the schemes, the authors conclude that single carrier environment is best suited for AANET.

2.5 Network Partition

In a network, a group of nodes exhibiting a collective behavior, which is different from the whole network, segments the network and creates network partition. Network partition affects the global behavior of the network. Tasks at the application layer of the network may be obstructed due to the emergence of groups in the network. Routing of packets is expected to be jittery, if after partition of the network, source and destination nodes belong to different partition. In mobile networks, partition of network is unavoidable mainly due to the mobility of the nodes. Mobile nodes depending upon their velocity and direction of motion, can change the topology of the network. This leads to the formation of partitions. When partitions are created due to motion, nodes in the partitions display 'group mobility'. The number of partitions created depends on how often a group of nodes change their direction of motion. Thus, predicting the number of partitions is an important key to maintaining the integrity of the network. Too frequent changes in the network topology needs restructuring of the network more often. Frequent restructuring of the network induces loss in the network, in terms of communication and other cost factors such as throughput and delay.

AANET is very dynamic in nature. In order for the network of aircrafts to be resilient, a stable topology must be achieved. In the multi-tier network of AANET, the layer one (ground) and layer three (HAPs and satellite) are relatively stable as compared to the mobile aircrafts in the layer two. Probability of reliable communication between aircrafts on the same flight path is higher than aircrafts flying in opposite directions. Such links formed are expected to last longer than links formed between aircrafts moving in opposite direction. Thus, aircrafts moving in same direction show a group mobility similar to 'bird flocking' in SWARM sensors. The efficiency of the AANET can be improved if a global knowledge of the network partition can be maintained. However, in the highly dynamic network, network monitoring is a challenging issue. For predicting partitions and also maintaining the coordination between them, the network should be able to identify the topology changes as soon as they occur. Following this, the routing decisions can be made accordingly to prevent link breakage and packet loss. The optimum level of 'self healing' can only be achieved with effective partition tracking. In the following section, we highlight the existing solutions, and propose a novel way to tackle the issue.

2.6 Network Partitioning in AANET

In "Global In-Flight Internet"[55] Sakhaee *et al.* suggest the clustering of aircrafts over continental masses. This clustering is an example of elementary network partition. The mobility pattern of aircrafts is different for inter-continental and intra-continental flight paths. Inter-continental flights such as those in the North Atlantic Corridor(NAC), have two major direction of motion. There is a collective East bound or West bound air traffic. Hence, the network has two separate mobility partition. However, for intra-continental flight paths, such group behavior cannot be observed. The changes is topology is more frequent than that of the inter-continental flights.

The NAC has been inspected by researchers for validating protocols in AANET communication. The group mobility of the aircrafts in NAC is well exploited for achieving long duration of links between aircrafts and to avoid packet drops. This can be seen in [42], where “greedy forwarding” is employed for delivering packets to the destination node. The authors call attention to 'stable' topology of AANET in NAC. This is possible because, the aircrafts maintain a uniform direction of flight. Once en-route and on appropriate *flight level*, aircrafts move in a common direction (East or West) and maintain a constant velocity for long durations in their fight. This makes the topology stable. For a particular source and destination, packets are always forwarded to the nodes closer to the destination. Since the aircrafts exhibit a group motion towards same direction, greedy forwarding is beneficial as relay nodes progressively move towards the destination. Another case where network partitions can be seen in play is in [65]. An aircraft's neighbors are divided into two groups: reachable and non-reachable nodes viz. adjacent-relay aircrafts (ARA) and distant-relay aircrafts (DRA). Subsequently, for routing packets to the destination, an aircraft may either greedily forward packet to a relay aircraft flying in same direction as with its own, or it can forward packet to an aircraft flying in opposite direction in case there are no nodes in the same direction. A third alternative is proposed, where the air space is equally divided into parts. Packets are greedily forwarded to nodes in the same part. First priority is given to the nodes flying in the same direction.

It is evident that group mobility is significant criteria which influences the routing decisions in the network. Hence, nodes should be aware of the current topology scenario of the network. However, keeping topology updates will require every node to cache position information about other nodes. This leads to obvious issue of maintaining large routing tables per node. Moreover, frequent topology updates can only be obtained from ground gateways or from satellites, which increases the dependence of the nodes on the infrastructure, increasing the cost of the system at the same time. This problem of flooding nodes with topology information is resolved in Greedy Perimeter Stateless

Routing (GPSR) [34] for wireless sensor nodes using *greedy* and *perimeter* forwarding of packets. The same idea has been adopted by Medina *et al.* in GLSR [42]. While greedily forwarding packets, in the absence of neighbor in the range, the source node becomes a *local maximum*, which means, it is the closest node to the destination. If it persists to be a local maximum, packets may be dropped if the source is far away from the destination. Medina *et al.* deal with this problem by increasing the range of communication of a node. By doing so, the neighborhood of each node is extended, accommodating more nodes in the range of a node and at the same time reducing its risk of becoming a local maximum. Perimeter routing is an alternative way to avoid local maximums in the network, wherein the packets are routed around the perimeter nodes of the source node following the textitright hand rule until a node closer to the destination is found, after which the routing switches back to greedy mode. This method, however, may not be fruitful in sparse network scenario as discussed by Shrirani *et al.* in [63]. Authors further study the success probability of greedy forwarding in unmanned AANET, by making use of quadratic estimations. They conclude that greedy forwarding alone is not sufficient for routing packet successfully to the destination, and suggest the use of greedy forwarding, along with other routing protocols to optimize routing in the network. Thus, following arguments regarding routing in AANET can be listed.

- Location assisted greedy forwarding in 3D mobile network fails for sparse network.
- In perimeter mode of routing, immediate node to the right of the source along the perimeter, may be heavily congested while the node at the end of the perimeter and closer to destination may be least congested and vice versa. Hence, packets may be dropped before they reach the destination.
- In case a node wants more topology updates than one hop neighbors, a node has to depend on the ground infrastructure or cache more neighbor information.

These problems can create bottlenecks in AANET when one looks at the entire global network and the airspace. In future, the AANET communication is expected to take place between aircrafts belonging to different airline services. Thus, we are looking at possible subnetwork communication [4][20] between aircrafts.

Thus, while the network is partitioned with respect to mobility of the nodes, congestion at each node also affects the routing decisions. To make the network more aware, perhaps one should be able to *train* the network, so that it adapts to these changes spontaneously. [69] is an example where network partition due to mobility is studied in the wireless ad hoc network. Effective partition prediction is the key focus area of this work. However, only the mobility of the nodes has been considered to predict the partitions in the network. We need a method, that would help us look at more than one scenarios at a time. Also, such a technique should be able to recognize the group behavior of the network and associate each node to it accordingly. To obtain such associative relation between a node and the network, we direct our attention towards the Fuzzy Set Theory. Fuzzy logic gives freedom to the data points to assume any value between 'true' and 'false' which means a node has the flexibility of either being true to some extent or false to some extent.

Intuitively, Fuzzy theory can be used to derive metrics for routing in the network. Marwaha *et al.* employ such method in E-AOFR scheme[41]. It is an ad hoc on-demand fuzzy routing scheme which uses *multi-objective routing* for the wireless MANET. A cost metric is derived by fuzzy partitioning of the network parameters, the same is utilized for making routing decisions. For selecting optimal route to the destination, a unique cost metric is designed using the capacity of a node's battery life, link stability, the buffer lengths in the relay nodes along with the number of hops between the relay nodes. A route request packet RREQ is flooded in the network. The RREQ contains all the information about the network parameters. On receiving RREQ packets from more than one relay nodes, a destination selects that route, whose cost function is minimum. Through selection of most optimum route, the fuzzy cost metric is able to minimize the end-to-end delay, improve the packet delivery ratio and enhance the battery lifetime.

Although E-AOFR considers a multiple objective routing metric, it is not able to monitor the change in status of a node with respect to the entire network. To facilitate this, we need a tool which will associate a node to the group behavior of the network.

The FCM clustering is another branch of fuzzy theory. It is used for analyzing large data blocks and finds use in techniques such as pattern recognition. Usually, the traffic generated in any network static or mobile is large. FCM clustering has found use in training the system to detect traffic scenarios in the network. Such examples can be seen in the literature. The network traffic can be analyzed through monitoring the traffic or congestion level at each node. Fuzzy logic has been used for active queue management in [19] and [48], for traffic modeling and prediction in [16] [33]. Liu *et al.* use FCM clustering [40] for predicting point-to-point traffic in static network by using a network administrator which then makes routing decisions depending upon the congestion level.

The fuzzy theory is a powerful technique for modeling any network. It gives the opportunity to optimize the network, using more than one metric at time. To the best of our knowledge, FCM clustering has not been used for modeling of 3D networks (static or mobile). The AANET is complex in nature and is governed by multiple properties. We propose to use the multiple parameter handling capacity of FCM clustering to our advantage and examine the possibility of making the network more aware through its use.

In the following section we present the important highlights discussed in the chapter.

2.7 Summary

AANET Attribute	***Existing solution*/theories**	***Comments***
Applications	Airborne Internet Military Survilience Free Flight and 4D Trajectory Management HAP Broadband Access	The utility of AANET gets limited due to its dependence on ground infrastructure and satellite resources. This issue can be mitigated if gateways exist in the airspace .
Network Architecture	MANET Centric Architectute MANET IP Centric Architectute MANET Sub IP Centric Architectute Cross Layer Architectute	Cross Layer Architecture can accomodate the MANET centric and MANET IP centric architecture. Any network architecture for AANET should account for existense of both cluster and mesh topology in the network.
Mobility Modelling	Random Way Point Mobility Model 3D Gauss Markov Mobility Model Improved Semi Gauss Markov Mobility Model Smooth Turn Mobility Model	Smooth turn mobility model is best suited for modelling AANET. It can be modified to obtain a 'mermory' sustaining system through Markov Process. The mobility models should also account for group mobility of the aircrafts.
Access Schemes	TDMA STDMA I-TDMA	The STDMA and I-TDMA is most suited for direct one to one communication between aircrafts. This can be supported at physical layer by smart antenna systems. Link layer scheduling can be optimum on use of single carrier.
Network Topology	Cluster Mesh	A mixed topology should be developed. A mixed topology can represent the AANET more realistically, where clusters and mesh of nodes can co-exist.
Routing protocols	Reactive Routing Hybrid Routing Geographic Position Based Routing Cluster Based Routing	Routing protocols should maintain the throughput of the network in events of network partition. Routinng protocols should enable priority routing and multiobjective routing for aircrafts, for serving QOS purposes.

Chapter 3

Proposed Network Monitoring Scheme for AANET

In the airspace, the aircrafts can either form a mesh network or they can form clusters. An aircraft (or simply denoted as "node") can be in one of the four states described in Fig. 3.1. An en-route aircraft, flying across the airspace can exist in "*idle state*", a "*mesh state*", a "*clustered state*" or in a "*migrating state*". The functions of each state are identified as follows.

- *Idle State:* A node in the idle state is not connected to the AANET. When "idle", a node does not participate in any routing task in the network.
- *Clustered State:* A node in a cluster of nodes is in "clustered" state. The node routes the data as a cluster member.
- *Mesh State:* A node, acting as a router in the mesh network of aircrafts is in "mesh state".
- *Migrating State:* In "migrating" state, a node is disconnected from the AANET. A node gets disconnected if it moves from one cluster to another or if the mesh network disassociates due to increase in separation between the aircrafts. Therefore, a node

continues to migrate until it is accepted in another cluster or as a link in the mesh network.

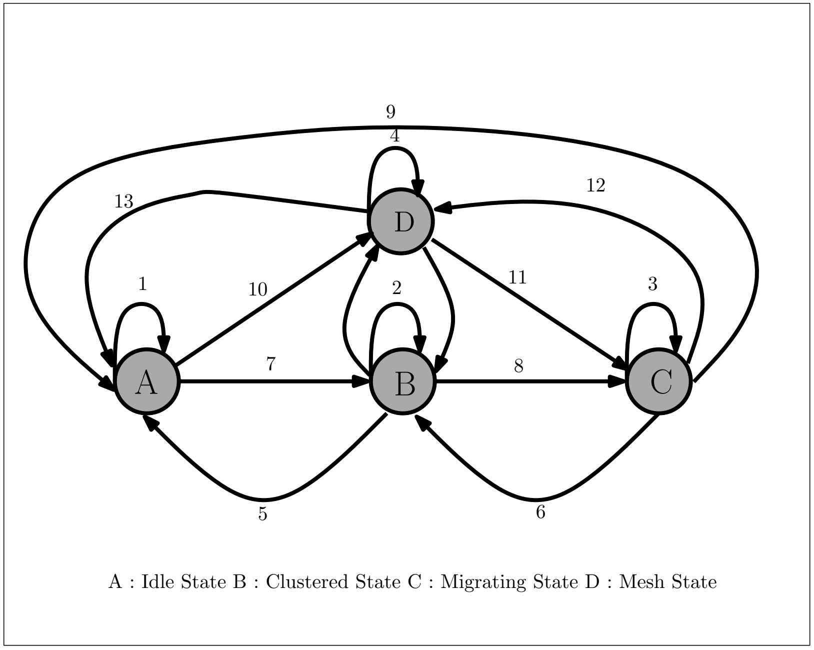

Figure 3.1: States of Airborne Node

Fig. 3.1 shows all the possible state transition an aircraft can make in AANET. An aircraft, initially in unknown state, can connect to AANET in two ways. The aircraft can become a member of a cluster, shown by link no. 7. The aircraft can also become a part of a mesh network, shown by link no. 10. The transition from mesh state to cluster state and vice versa is attained by migrating. Link no. 8 and 11 depict the transition of aircraft into migrating state. The migrating state accounts for the period of disconnectivity, during which an aircraft makes the state transitions. The other transiting links, depicted in the figure, show the possibility of an aircraft remaining in the same state. The links also depict the transition of an aircraft back to same state before a transition was made.

Maintaining the connectivity in the AANET is the principal focus. Hence, "knowledge" of the network is an important criteria. Every aircraft cannot retain the information about the entire surrounding network. A priori knowledge of the network is always beneficial for improving network performance. Thus, getting topology update of the network is essential. In the present scenario, aircrafts depend on the ground infrastructure for receiving topology updates. Alternatively, ADS-B messages can be used to receive network topology information. This means that an aircraft can obtain information regarding other aircrafts which are in its communication range. To obtain a better perspective of the network changes, without depending on the ground infrastructure, we need a monitoring agent in the airborne layer which can effectively replace the need to depend on the ground and satellite resources. Thus, the need to monitor the airborne network arises, such that the monitoring can be done in airborne layer itself. Also, the monitoring should help in acquiring a view of the entire network and simultaneously inform the aircrafts in the network regarding the changes occurring in the network. In this chapter, we present a monitoring scheme for AANET. We also identify an agent which can assume the role of a network administrator in the airborne layer. Table 3.1 presents a list of symbols used in this chapter.

Table 3.1: Notations and their Meanings

Symbols	Meaning
H	Higher Altitude Platform
VC	Voronoi cell
S_r	Spherical Region
i	Iterator

Section 3.1 presents our network model and elaborates on the network monitoring scheme.

3.1 Network Model

3.1.1 Voronoi Space Partition

The AANET is spread across the airspace at various FL. To observe the topology change across the vertical and horizontal span of the airspace, a flexible structure is required for observing changes in the 3-dimensional geometry of the network. We propose a Voronoi space partition of the airspace. Mathematically a Voronoi diagram divides a space containing points into regions. Each region or cell is created using a generator seed or point. Points are said to be in one region if they are closest to the generator seed. This is called shortest point Voronoi diagram. On creating Voronoi space partition of the airspace, we achieve smaller observing cells for observing the airspace. All aircrafts closer to the generator seed will be in same Voronoi cell. This creates a 3-dimensional space partition in the airspace. The Voronoi space tessellation can be used to partition airspace above the continental masses and oceanic surfaces. We assume that every Voronoi cell, VC_i, is generated by using a Higher Altitude Platform, H_i, as the generator seed. The aircrafts closer to the generator HAP belong to the respective Voronoi cell VC_i. Consider the geographic location of North Atlantic Corridor (NAC). The airspace above NAC hosts the world's busiest air traffic. The collective flight direction is towards eastbound routes and the westbound routes. Fig. 3.2 depicts a Voronoi space tessellation model of the NAC. In every Voronoi cell, the HAP is placed as shown in the figure. Therefore, a strategic placement of the HAPs can help to cover the entire airspace over the corridor.

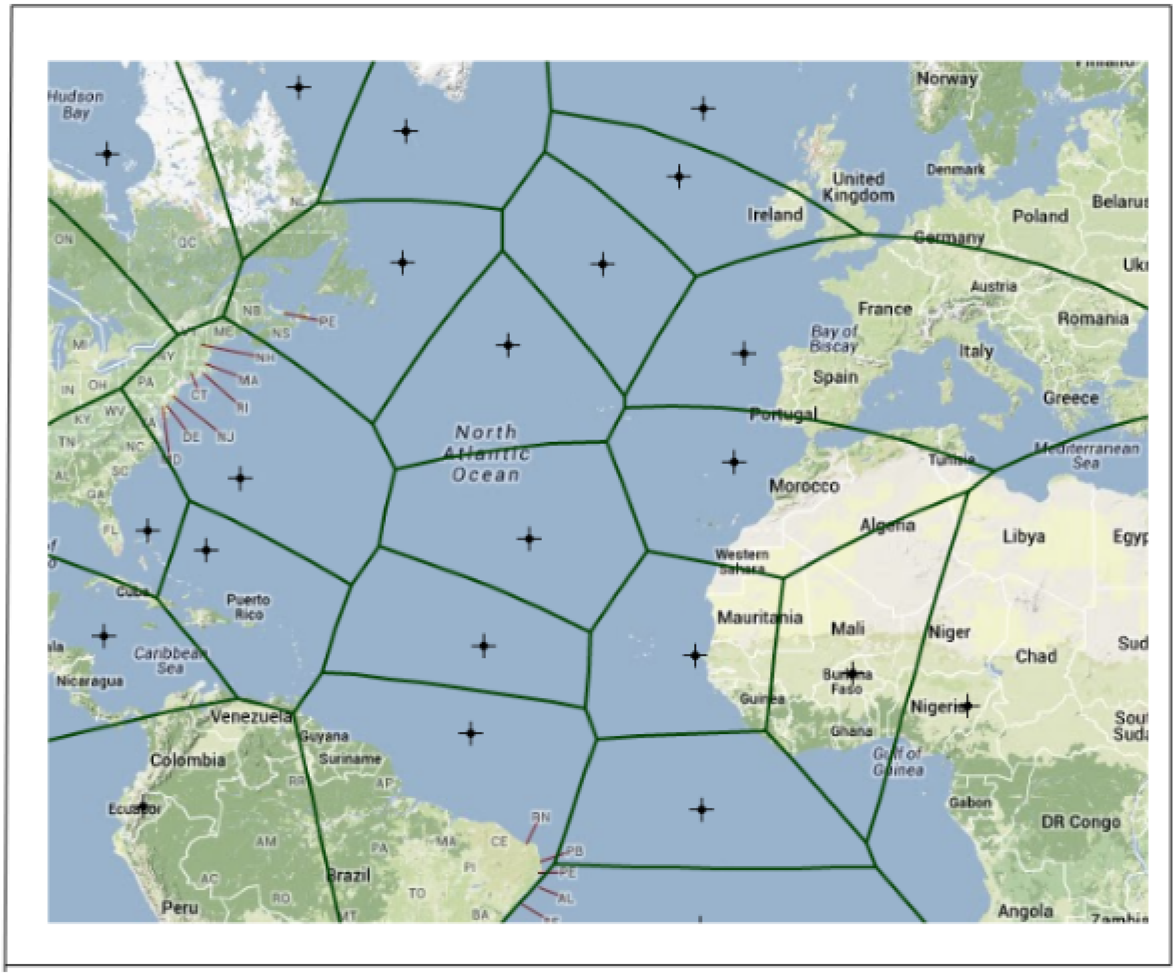

Figure 3.2: Air Space Partition

The HAPs fly at much lower velocities relative to the aircrafts flying at standard flight levels. Since the HAP is considered as the generator seed for the Voronoi space tessellation, the cells have stable structure. This is because the slow movement of the HAPs leads to a very gradual change in the space tessellation and does not affect the network monitoring. Section 3.1.2 is a discussion on HAPs and their role as network administrator in our network model.

3.1.2 Airborne Network Administrator: HAP

A Higher Altitude Platform (HAP) is an aerial vehicle equipped with communication payloads. The HAPs are positioned in the stratosphere at heights of 17-22km. This height is much lower than those of geostationary satellites, which are positioned at orbital heights of approximately 40,000km above Earth's surface. The HAPs are flown in tight circles making them quasi stationary with respect to other aircrafts. This means relative to the aircrafts they appear stationary. The HAPs are being examined for realizing broadband communication services over the terrestrial network. Some projects commissioned for achieving wireless broadband communication using HAPs and surveillance related operations are the HALO Network [17], the HeliNet [64] and the HELIOS [45]. The key characteristics of the HAP which makes them an important element in the heterogeneous network are listed below.

a. The HAPs are positioned closer to the aircrafts as compared to satellites. Hence, the round trip delay (250ms for communicating with satellite) involved in communication is less. They provide means to reduce dependence on the ground infrastructure.

b. The HAPs can provide large area of ground coverage with cell diameters reaching up to 200km.

c. The HAPs have both unicasting and multicasting capabilities in the network.

d. The HAPs can be easily deployed and they can communicate using the existing communication infrastructure.

We use the above properties of HAP to our advantage and propose a layer of quasi stationary HAPs in the airspace. The layer of HAPs form a network of connected network administrators in themselves. The administrators can exchange information using radio links or FSO links. The 28/47GHz band in the spectrum is allocated worldwide for the HAPs. In our network model, in every Voronoi cell VC_i the HAP acts as the network administrator. As a network administrator the HAP's responsibility is to accumulate data from network members, analyze the data and get an overview of the network in its cell.

Fig. 3.3 represents our complete network model.

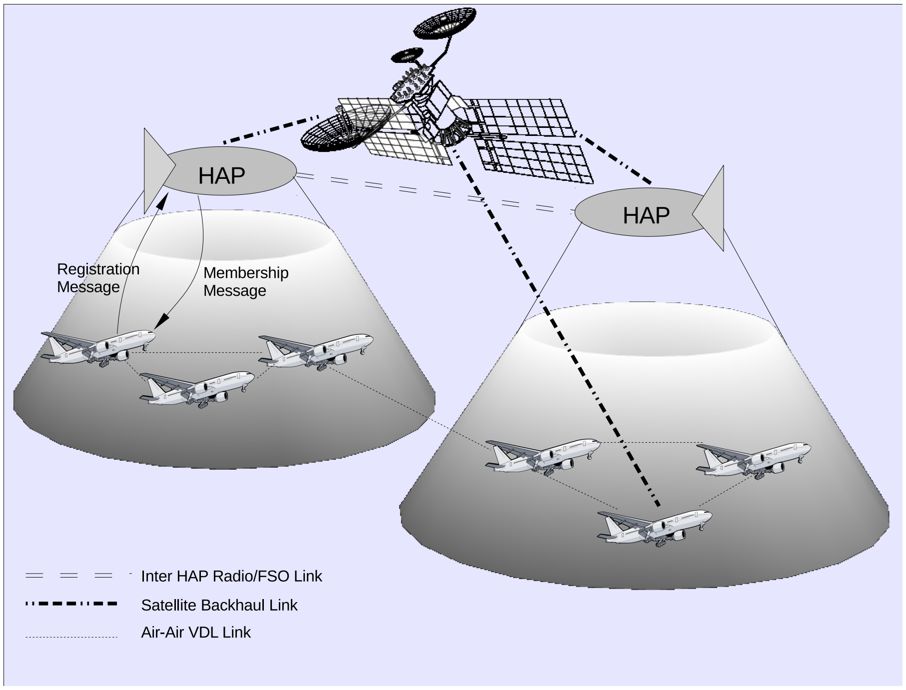

Figure 3.3: Network Model

In section 3.2, we present our monitoring scheme for the AANET.

3.2 AANET Monitoring Scheme

---

1. Airspace is divided into 3D Voronoi cells.
2. A HAP H_i provides service in each cell VC_i and acts as the network administrator.
3. Aircrafts in a Voronoi cell VC_i register with their respective HAPs H_i.
4. The HAPs collect position, velocity and congestion updates from aircrafts in their cells.
5. The HAPs run a data analysis process in their respective Voronoi cells periodically.
6. The HAPs returns a status update to every aircrafts in the cell.

We make the following assumptions regarding the AANET.

1. For the AANET, source and destination are in the airborne layer.
2. The AANET comprises of clustered aircrafts or a mesh network of aircrafts. Ideally, the clusters and the mesh network are connected.
3. There is some data traffic in every aircraft which is connected to the AANET.

Section 3.3 presents our discussion on network monitoring in a Voronoi cell VC_i.

3.3 Monitoring Process

The proposed network monitoring scheme is a two-tier process involving:

1. Aircraft registration,
2. Network supervision by the HAP.

The registration of aircrafts and supervision is a periodic phenomena. The aim is to identify the topology change in the network with minimum delay and prevent periods of disconnectivity in the AANET. Fig. 3.4 depicts the aircraft registration process.

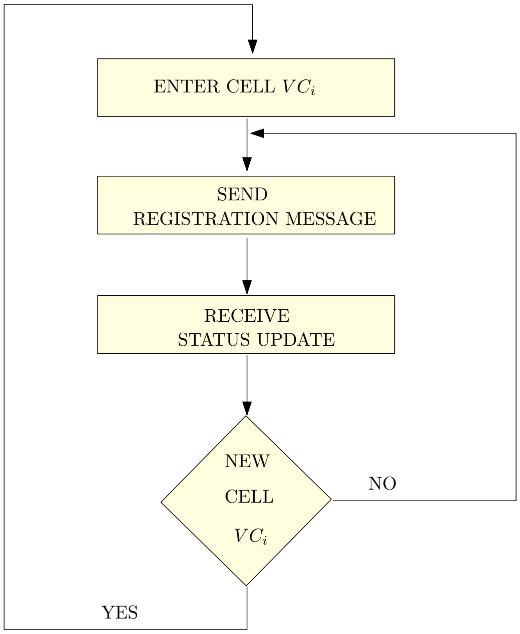

Figure 3.4: Aircraft Registration

The network is monitored separately in every cell. The HAP keeps the record of current network scenario in the cell. Therefore, when an aircraft enters a new cell it has to first inform the HAP regarding its presence. Thereafter, it can receive information about the network from the HAP. The registration process is carried out by sending registration messages to the HAP. The proposed format for the registration message is depicted in Fig. 3.5. It is assumed that all the aircrafts are time synchronized. The registration message is issued with a time stamp and aircraft's ID. The time stamp helps the HAP to keep a track of latest registration message from an aircraft. The position and velocity of the aircrafts are essential for determining the topology change in the network. With every registration message, the aircrafts convey their current velocity and position information to the HAPs. The buffer occupancy of each aircraft is also send with the registration message. Every aircraft sends the registration message periodically to the HAP in the cell. When an aircraft enters a new Voronoi cell, it registers itself with a new HAP.

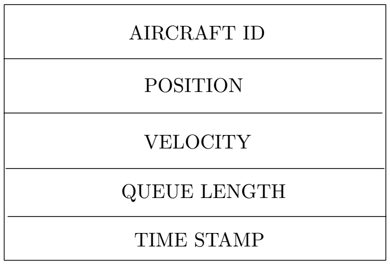

Figure 3.5: Registration Message

The periodic registration messages sent to the HAP ensures tracking of all every aircraft in the cell. Aircrafts in every state (idle, clustered, migrating or mesh) are expected to send the periodic registration messages. The HAP ID is a means to identify the Voronoi cell. When an aircraft passes from one cell to another the HAP ID included in the status update message not only gives the network statistics in the cell, but the new HAP ID also informs the aircrafts of its handover to the new network administrator. The HAP in the cell always updates its network database. The main idea behind periodic tracking is, to acquire network statistics from the aircrafts. With frequent updates from the aircrafts in the cell, the HAP can easily monitor the change in the topology of entire network. The knowledge of the network change should be reverted to the aircrafts in the cell. This is done by giving periodic status updates to the aircrafts in the cell. The status update message is also issued with a time stamp and the HAP ID. The time stamp is included to ensure that aircrafts update themselves with the latest network changes. The change in the Voronoi cell should not affect the connectivity of the aircraft in the AANET. Fig. 3.6 outlines the task of network supervision carried out by the HAPs.

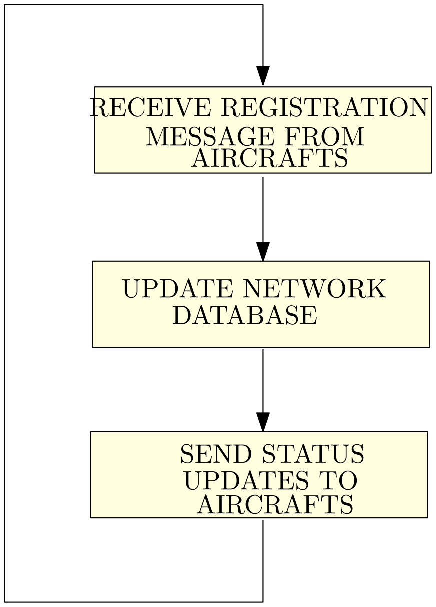

Figure 3.6: Network Supervision by HAP

The advantage of having a monitoring agent can be utilized by the aircrafts in the network in two ways: (1) when an aircraft is in the idle state, and (2) when an aircraft is in the migrating state. An aircraft in ideal state has no knowledge of the network. In such scenario, the aircraft can request the HAP providing service in its cell for topology update. The second scenario arises, when an aircraft transits to the migrating state. In the migrating state, an aircraft gets disconnected from the network. This disconnection leads to route disruption in existing communication between source and destination. A route disruption implies that more than one aircraft may get disconnected at a time. This eventually may disintegrate a cluster of aircrafts or a mesh of aircrafts. To restore connectivity in the AANET, a migrating aircraft should be immediately directed to regions of the AANET where it can be accepted with minimum delay. That is, instead of broadcasting join requests in the entire network, an aircraft should send join requests to those regions where the probability of being accepted in the AANET is higher. This knowledge can be provided by the HAP in a cell, as it maintains a record of the network statistics. Thus, time and resources involved in broadcasting join requests over entire network can be mitigated. This will also prevent excessive flooding of network with join requests. Thus, an inquiry made by an ideal or migrating aircraft is responded by a "network information". This perception can be physically realized by giving antenna rotation directions to the aircrafts. That is, an aircraft can effectively broadcast join requests in a specific region of the airspace where it can get easily absorbed in the AANET. To have a complete overview of the cell the HAP as to monitor the topology change and the data traffic in its cell across all flight levels (FL). This can be done by analyzing the time variant topology change and data traffic in the AANET received through the status update messages. Section 3.4 elaborates on the primary network changes, the HAP needs to identify in a cell for maintenance of the AANET.

3.4 Cell Behaviour

3.4.1 Mobility Groups

The AANET is highly dynamic due to high ground speeds of the airborne vehicles. Although the ground speed of air vehicles is high, it has been indicated in the literature that the constant flight speeds makes it possible to achieve a stable network amongst the nodes. This is however limited to network formed at same flight levels extending over short area or tunneling between aircrafts and ground station across the vertical airspace. To achieve a connected network across all FL, the difference in the velocities and direction of the aircrafts need to be examined more carefully. A network of aircrafts flying at different FL shows group mobility. This is mainly due to the difference in direction of flight paths and the velocities. A minor change in the velocity of aircraft can affect the link between two nodes. This due to change in their relative velocities. Over a large stretch of airspace like the NAC, the mobility groups are distinct and less in number. The group mobility of aircrafts flying over intra continental routes is more random in nature. Thus, one can expect more mobility groups in such flight routes. A "mobility group" is a group of aircrafts headed in a common direction. The mobility groups create distinct partitions in the network. The topology change in the network can be attributed to the change in the group mobility of the aircrafts. In a region of airspace, one of the following events may occur pertaining to the mobility groups mg_i.

- Two or more mobility groups may merge together.
- An existing mobility group may disintegrate into more mobility groups.
- New mobility groups may be added in the region.
- All mobility groups may cease to exist in the region, due to movement of aircrafts into another region.
- An aircraft can switch from one mobility group to other.

Fig. 3.7 depicts four mobility groups having different directions of motion. The HAPs responsibility is to identify such mobility partitions in the network. As seen in the figure, the mobility groups may have varying aircraft densities. Also, some aircrafts may not be part of any mobility group, as seen in the figure. These aircrafts are "isolated" as they do not show a group behaviour. The group mobility of each group is represented using a group mobility vector as seen in the figure. The group mobility vector is a means to identify the common direction of flight in the aircrafts. As the position and velocity of aircrafts change, the change in group mobility vector can be used to identify the topology change in a of a group of aircrafts. However the group mobility vector alone is not sufficient to direct an idle aircraft or migrating aircraft for sending join requests to the AANET.

In section 3.4.2, we introduce the term "Directional Mobility" to identify the aircrafts in a mobility group that have higher tendency of forming an AANET.

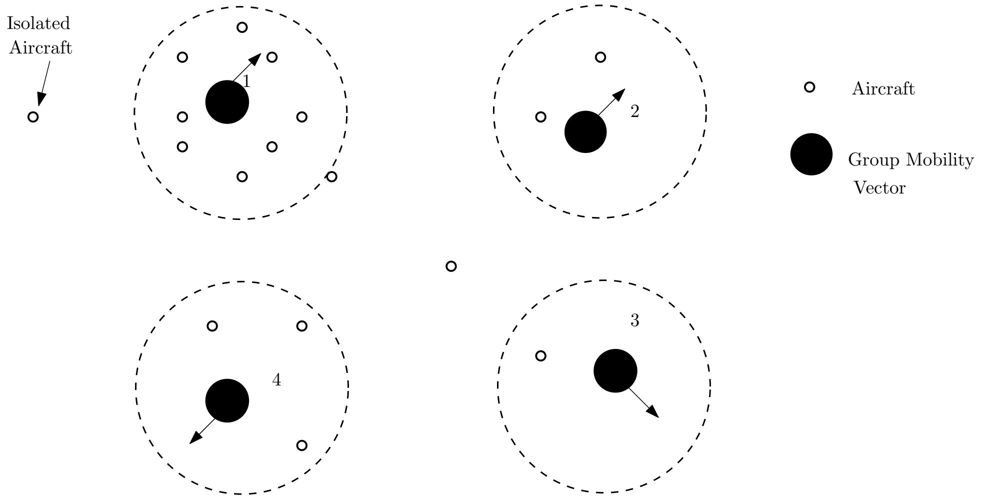

Figure 3.7: Mobility Groups

3.4.2 Directional Mobility

The mobility groups only help in distinguishing the direction of flight for a group of aircrafts. They however do not give a clear perspective of which aircrafts can actually form an AANET. This is because, aircrafts in the same mobility group may be separated from each other by large distance in the airspace. If the separation is beyond the maximum range of communication between the aircrafts, an AANET link cannot be supported. Thus, a mobility group and a closely spaced group of aircraft are two different aspects of the AANET topology. A group of closely spaced aircrafts demonstrate a directional behaviour, if they are in same mobility group. Therefore, we define, *Directional Mobility* as the directional behaviour demonstrated by aircrafts in permissible range of communication. As a network administrator the responsibility of HAP is to identify this directional behaviour in their respective cells. For analyzing the data traffic in the cell, the HAP has to distinguish between various congestion levels that might exist in the cell. In section

3.4.3, we introduce the concept of congestion class in a cell.

3.4.3 Congestion Class

In air-to-air communication between aircrafts, the traffic generated in each aircraft depends on the number of links associated with it. An aircraft is essentially a router. The data traffic generated can be due to different applications. The congestion in each aircraft is a measure of its availability to route packets in the network. The congestion in each aircraft depends on the time period spent by each packet in the queues. That is, the queuing delays influence the congestion in each node. Therefore, in a group of aircrafts forming a network, the congestion in individual aircrafts affects the connectivity. It is essential to monitor the topology change, and the congestion at the same time. This is because the probability of an aircraft being accepted into an existing AANET largely depends on the "availability". An aircraft becomes congested if the packet arrival rate is more than the delivery of the packets through it. This may happen if it takes longer to find a relay aircraft or the destination aircraft. Although the end to end delay while transmitting data packets can be reduced by queue management techniques, the arrival rate of packets at every aircraft leads to differential congestion in the network. While some aircrafts may be highly congested, some may be handling very low data traffic. Therefore, we define a *congestion class* as threshold congestion level in the aircrafts such that two or more aircraft can have same, or a congestion level nearer to this threshold. Therefore, a differential congestion in the cell will lead to the existence of more than one congestion class. Section 3.5 presents our discussion on identifying data analyzing techniques that can be used by the HAP to monitor the directional mobility and congestion classes in the cell.

3.5 Network Analysis

The cell behavior points out three primary criteria which affects the connectivity in a network of aircrafts and can be listed as follows.

- Proximity of the aircrafts.
- Direction of Flight.
- Congestion in individual aircrafts.

The change in network statistics can be observed by analyzing the registration messages. The registration messages not only carry necessary topology updates and data traffic in the cell, but they also inform the HAP regarding the density of aircrafts in the cell. The HAP's responsibility is to identify the directional behaviour and the congestion classes in the cell with the varying network density. In order to distinguish the partitions in the network, the HAP needs to disassociate the position and velocity information of the registered aircrafts into 3 dimensions. The primary objective behind this disassociation is to identify the group mobility vectors in the 3 dimensional geometry of the cell and the directional behaviour in them which means that the HAP should be able to monitor the network across all the 3 dimensions. An aircraft's position and heading are denoted using latitudes and longitudes. To emulate this effect we use the 3D position vector for representing aircraft's elevation (z coordinate) and movement in same flight level (position in x-y plane). The aircraft's heading is obtained from the velocity vector. This done by transforming the Cartesian axes to spherical coordinate system. The azimuth angle gives the movement of aircraft on a flight level. The elevation angle represents the heading of aircraft in the vertical airspace. Therefore, every Voronoi cell can be monitored in terms of *spherical regions*.

In this work, we have mapped the aircrafts in three spherical regions. Table 3.2 presents the spherical regions with their respective azimuth and elevation angles.

Table 3.2: Spherical Regions

$Spherical Region$	Azimuth (deg)	Elevation (deg)
1	0-120	0-90
2	120-240	0-90
3	240-360	0-90

To understand the implications of network partition in the AANET, we simulated a mobility scenario of aircrafts in Network Simulator 3(NS3) using 3D Gauss-Markov mobility model [13]. Fig. 3.8 is a snapshot of the network topology observed at an interval of 100 seconds. Fig. 3.9 represents the corresponding velocity vectors of the aircrafts in the 3D coordinate axes. Fig. 3.10 is the representation of velocity vectors in the 2 dimensions.

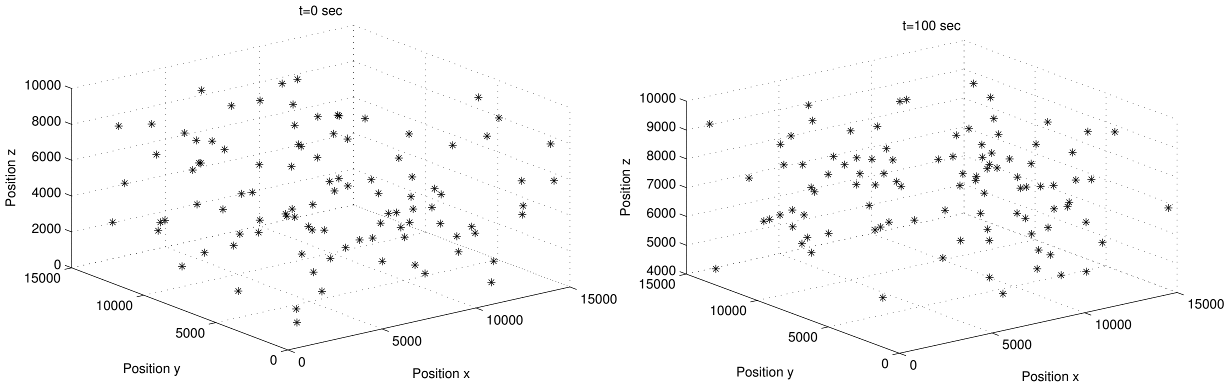

Figure 3.8: 3D Projection of Aircraft Position

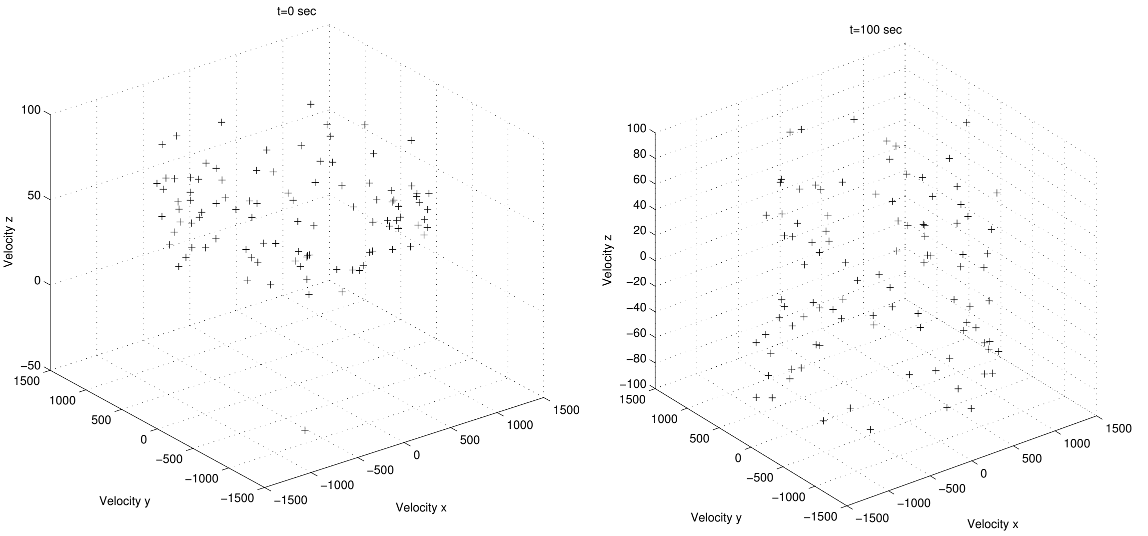

Figure 3.9: 3D Projection of Mobility Groups

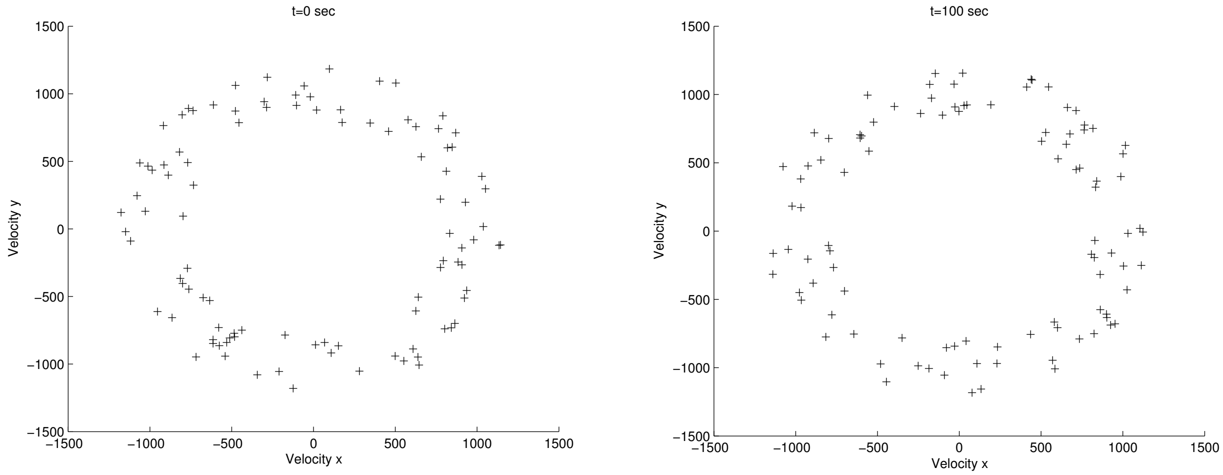

Figure 3.10: 2D Projection of Mobility Groups

The 3D position plot clearly highlights the elevation of the aircrafts (z axis). At the same time the mobility projection in x-y plane accounts for flight direction in same flight levels and the 3D mobility plot accounts for an aircrafts heading in accent or descent. From the position and velocity plot it can be observed that a group of aircrafts which seemingly appear as a cluster in the airspace, have different mobility projections. This supports our notion that directional behavior in the AANET can not be recognized by group mobility alone. A group of aircrafts that can be represented using a group mobility vector forms a "cluster". Similarly a group of aircrafts having a common congestion threshold forms a cluster. Thus, the HAP has to identify the group mobility vectors in its cell. Thereafter, establish the association of every aircraft in the cell with these vectors. Therefore, the network administrator needs a efficient data analyzing technique for "translating" the physical geometry of the network in its database. Given which, it can identify the required clusters from the available network statistics. From the perspective of AANET, following is expected of any data analyzing scheme used for monitoring the network by the HAP.

- The data analyzing scheme should track the topology change in the AANET.
- It should identify the switching of aircrafts from one mobility group to another.
- It should clearly establish the association of aircrafts with the changing group mobility vectors and the congestion thresholds.
- Isolated aircrafts should also be tracked.

The observations imply that an en-route aircraft can not be associated with a single cluster. Restricting an aircraft to a single cluster will lead to formation of "hard clusters". This is a common terminology used in data clustering techniques, used for classifying data with common characteristics, which do not change over time. It is not reasonable to form hard clusters of aircrafts because the group mobility vectors and congestion thresholds in the cell are not constant. Also formation of hard clusters can not associate the isolated aircrafts with the changing group mobility vectors and congestion thresholds. A more appropriate choice is to form "soft clusters". A soft clustering of data allows association with more than one cluster in the data space. Therefore, we choose Fuzzy C Means data clustering as a means of translating physical geometry of the AANET, and at the same time track the changes in network statistics.

Fig. 3.11 represents the idea of network analysis, as an integeral part of updating network data base by the HAP.

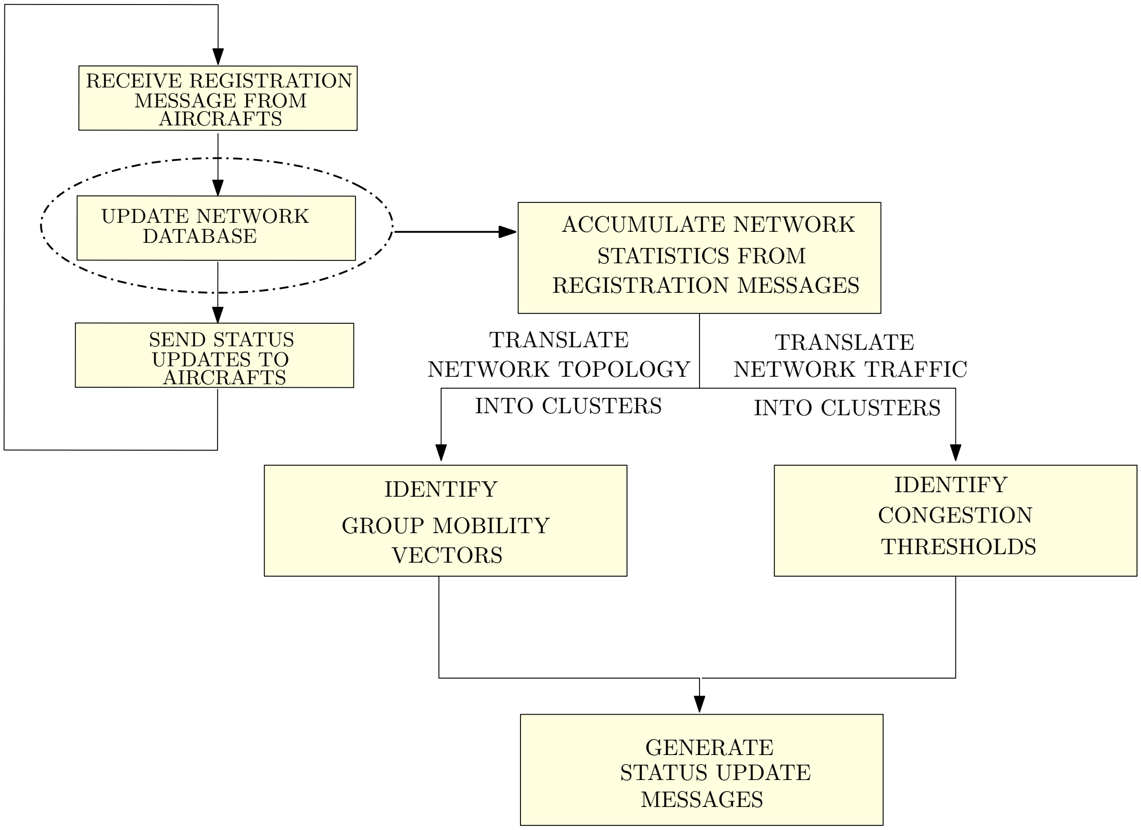

Figure 3.11: Network Analysis

3.6 Summary

In this chapter the network monitoring scheme for the AANET has been provided. For monitoring and observing the 3-dimensional topology change of the network we partition airspace using the Voronoi space tessellation. The HAPs are chosen as the generator seeds for generating the Voronoi cells. They also act as the monitoring agent or the network administrator in their respective cells. The network monitoring is carried out by HAP through reception of periodic registration messages from the aircrafts. On reception of these registration messages the HAP is expected to identify the directional mobility and congestion classes in the cell. These network statistics are reverted back to the each aircraft until it changes its cell. The aircraft is handed over to new HAP, once it changes its Voronoi cell. The HAP always updates it self with topology change in the network of its cell and maintains a record of all the registered aircrafts. The quasi stationary HAP layer in the AANET can communicate with each other through radio links or FSO links. The satellite links are used as backhaul support in case the inter HAP link fails or the AANET air-to-air link fails ensuring connectivity in the network.

Chapter 4

Network Awareness Using Fuzzy C Means Clustering

The FCM Clustering algorithm incorporates ideas of fuzzy theory. It was developed by Dunn and subsequently improvised by Bezdek [10]. The FCM clustering process is used for analyzing and clustering large data blocks due to which it finds use in applications of pattern recognition. The FCM technique can be both possibilistic and probabilistic. The algorithm receives a data set and a predefined number of clusters, in which the data set is to be divided. At the end of the FCM process, each data point in the set is associated with all the available clusters with some "degree". This degree is termed as "membership" to individual clusters. This means that a data point belongs to multiple clusters rather than one. The clusters are obtained by iterative partitioning of the data set. The process terminates when the objective function J_m given by Eqn. 4.1 is minimized.

$$J_m = \sum_{j=1}^{N} \sum_{i=1}^{C} \mu_{ij}^{m} \|x_i - c_j\|^2 \tag{4.1}$$

$1 < m < \infty$

Here, m is the fuzzyfication factor, N is the total number of data points in the set, C is the number of cluster centers, and μ_{ij} is the membership of data point N_j with cluster center C_i. μ_{ij} is obtained using Eqn. 4.2. The objective function is minimized with respect to the Euclidean distance between the cluster center C_i and the data point N_j. That is, for a given given cluster center C_i, data points closer to it will have higher membership values.

$$\mu_{ij} = \frac{1}{\sum_{k=1}^{C} \frac{\|x_i - c_j\|^2}{\|x_i - c_k\|^2}^{\frac{2}{m-1}}} \tag{4.2}$$

such that

$$\mu_{ij} \in [1, 0], \ \ \forall i, j \tag{4.3}$$

$$\sum_{i=1}^{C} (\mu_{ij}) = 1, \ \ \forall j \tag{4.4}$$

Eqn. 4.4 implies that every data point necessarily belongs to at least one cluster, and hence, is not isolated.

$$c_i = \frac{\sum_{k=1}^{N} \mu_{ij} \cdot x_i}{\sum_{k=1}^{N} \mu_{ij}} \tag{4.5}$$

$$\|(\mu_{ij})^{(k+1)} - (\mu_{ij})^{(k)}\| \leq \epsilon \tag{4.6}$$

The FCM process starts with the initialization of the partition matrix $\mu_{ij}(0)$, at step k the cluster centers are updated using Eqn. 4.5. μ_{ij}(k) is updated using Eqn. 4.6, and the FCM process is repeated until it converges or Eqn. 4.2 holds.

The following example demonstrates FCM clustering on an one-dimensional data vector **D**.

Example: The FCM Clustering.

Let **D**=$\{2, 4, 6, 5, 10, 21, 35, 12, 60\}$ be a set, containing one-dimensional data points D_j. Let the number of cluster centers be 3; thus, **C=3** and **N=9**. For **i** ϵ[1,3] and **j** ϵ [1,9], the partition matrix μ_{ij} of dimensions $\{$**3X9**$\}$ is obtained as follows.

$$\mu_{ij}^{(0)} = \begin{pmatrix} \mu_{1,1} & \mu_{1,2} & \cdots & \mu_{1,9} \\ \mu_{2,1} & \mu_{2,2} & \cdots & \mu_{2,9} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{3,1} & \mu_{3,2} & \cdots & \mu_{3,9} \end{pmatrix} \tag{4.7}$$

The FCM clustering begins at Step 0. Partition matrix $\mu_{ij}^{(0)}$ is initialized with random values. Eqn. 4.5 is used to obtain the first set of cluster centers C_i. Eqn. 4.1 is used to obtain the objective function $J_m^{(0)}$. Eqn. 4.2 updates the partition matrix to $\mu_{ij}^{(1)}$. In Step 1, if $\|\mu_{ij}^{(1)} - \mu_{ij}^{(0)}\| < \epsilon$, the process terminates; otherwise, it continues until the objective function J_m converges. For the above data set **D**, the first iteration gives $J_m^{(0)}$=1032.7303194365. As the FCM process converges, the objective function is progressively minimized and ceases to change. For the above data set **D**, the values of objective function in the last two iterations are: $J_m^{(f-1)}$=147.0620247842 and $J_m^{(f)}$=147.062016631. At the end of FCM process, the cluster centers obtained are: C_1=6.5098 C_2=59.8971 C_3=29.7020. The final values of membership assigned to the **9** data points are the following:

$$\mu_{ij}^{(f)} = \begin{pmatrix} 0.9684562427 & 0.9885797311 & \cdots & 3.69X10^{-006} \\ 0.0058761572 & 0.0019931266 & \cdots & 0.9999847939 \\ 0.0256676001 & 0.0094271423 & \cdots & 1.15X10^{-005} \end{pmatrix} \tag{4.8}$$

For $D_1 = 2$, $\mu_{ij} = 0.9684562427$, implying that it is closer to center C_1.

The notations used in this chapter are presented in Table 4.1.

Table 4.1: Notations and their Meanings

Symbols	Meaning
J_m	Objective Function
m	Fuzzification Factor
μ_{ij}	Membership Function
C	Number of Cluster Centers
N	Number of Data Points
i, j, k	Iterators
D	1-Dimensional Data Set
X	Data Object
x	P-Dimensional Data Vector

4.1 Using FCM Clustering for Monitoring AANET

The FCM can be a very convenient tool for analyzing mobile networks. The perk of this clustering process is that the objects can be analyzed by examining more than one property. A membership value can be associated with every property.

If FCM clustering is employed to cluster X data objects, then each object can be represented by a data vector "x", where every data vector "x" represents a set of **P** properties of a mobile node such that it can be represented in a P-dimensional space. For P $\leq$ 3, the objects can be represented in a space, of up to 3 dimensions (Fig. 4.1).

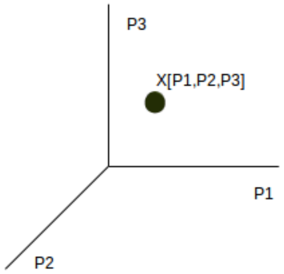

Figure 4.1: P Dimensional Data Vector

Let the set X_j= { x_1,x_2, . . . , x_N } represent the set of data vectors corresponding to all the airborne nodes. Here, each data vector represents P properties of each airborne node. For example, P can be 4 for an airborne node representing the following:

- Elevation or the flight level.
- Velocity and direction of flight.
- Position with respect to latitude and longitude.
- Congestion in the aircraft.

Using Network Simulator 3 (NS3), we obtained the mobility traces of a group of aircrafts. The 3D Gauss-Markov mobility model [13] was utilized for generating realistic position and velocity data vectors. The position and velocity data vectors are represented using the 3D Cartesian coordinate system. The nodes were simulated with velocity range up to 1200m/s. This velocity range fairly represents the high ground speed of the airborne nodes. Commercial aircrafts have cruising speed in the range of 450 to 560mph while military aircrafts fly with cruising speed of 1500mph and above. Our choice of velocity for the airborne nodes encompasses this supersonic speed of the aircrafts. The nodes are allowed to move in an area of 15km x 15km. The maximum height has been limited to 10km, to emulate the cruising altitude below the Stratosphere. The simulation setup is listed in the Table 4.2.

Table 4.2: NS3 Simulation Setup

OS	Linux (Ubuntu 13.04)
$Simulator$	Network Simulator 3
$MobiltyModel$	3D Gauss-Markov
$PositionAllocator$	Random Box
$SimulationArea$	15km X 15km x 10km

To identify the mobility groups and observe the directional behavior a FCM clustering analysis was done on the position and velocity data vectors. The FCM analysis has been done using MATLAB R2013a. We imported the topology update of the network from NS3 into MATLAB and then utilized MATLAB's **fcm** function for doing FCM analysis on the data vectors.

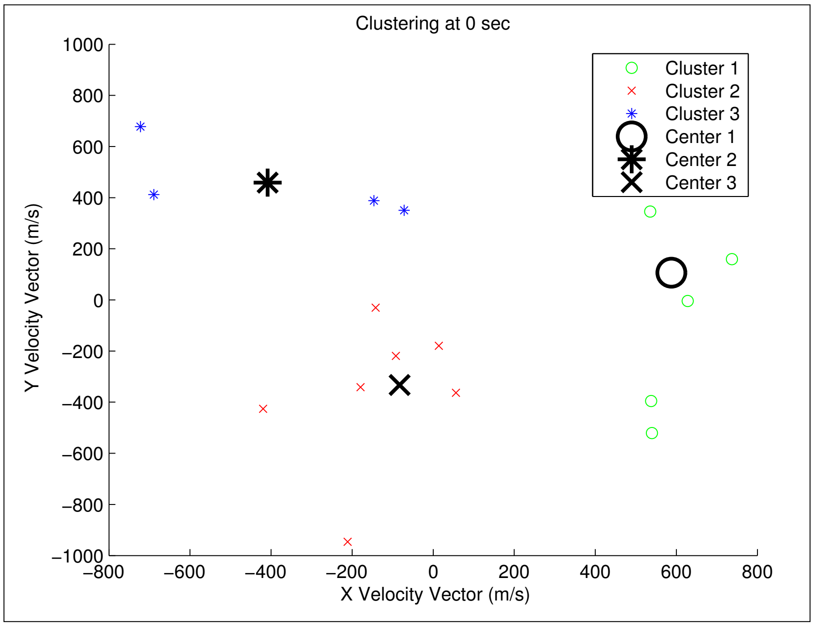

Figure 4.2: Initial Cluster Centers for Velocity Vector.

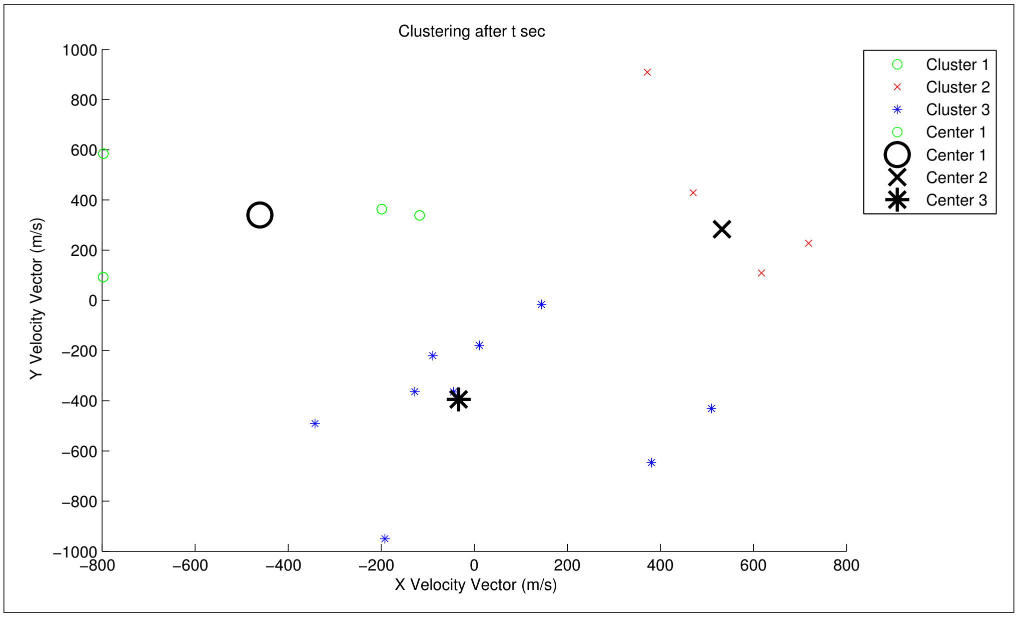

Figure 4.3: Cluster centers at t sec for Velocity Vector.

We monitored three mobility groups (position, velocity, and congestion) using FCM clustering. Our primary aim here was to observe the network partition in terms of instantaneous position of the airborne nodes and their direction of motion. By doing repetitive FCM clustering on the position and velocity data vectors, we tried to observe the change in topology of the network in x, y and z directions. The repetitive clustering is equivalent to periodic data analysis done by a HAP H_i in its cell VC_i. This essentially emulates the monitoring of cell VC_i by HAP H_i. Fig. 4.2 and Fig. 4.3 are the 2D plots of velocity data vector in x and y directions. The cluster centers found using FCM clustering has been marked in each figure. The centers represent the group mobility vectors of each group of nodes. The change in direction of a group of nodes can be estimated by observing the change in direction of the vectors. The number of nodes populating each group clearly demonstrates the partitions created in the network due to the change in direction of motion of the nodes. It can be seen that, although the group motion continues to be in the same direction the number of nodes moving in particular direction changes. This validates our idea of monitoring the topology change in the cell VC_i.

Since an aircraft is oblivious to the network changes occurring globally in the cell, it is the HAP's responsibility to inform each node or aircraft about the changes occurring in the network. In the cell VC_i, the HAP H_i is in charge of giving status updates to the registered aircrafts. These status updates give every node the information about network status in the cell. Given the status updates, every node can identify its status with respect to other nodes or a group of nodes. The periodic registration messages received by the HAP, contains the current position, velocity and congestion status of every node. The FCM clustering proves to be handy for monitoring the changes in these network statistics. The topology updates in a cell are accumulated by the HAP. A FCM clustering run on the data vectors helps in identifying the group mobility vectors and the congestion thresholds in every cell. This is done by finding the cluster centers. Since the cluster centers represent the partitions in the network, they can be equivalently termed as the partition center **PC**. Thus, over a time period, the change in partition centers reflects the change in network in the cell. The HAP can globally monitor the movement of each mobility group and the number of nodes populating them.

For understanding the implications of FCM clustering on the registration messages in a cell, we simulated a small group of nodes. The movement of nodes was observed for a period of 1000 seconds. Table 4.3 represents partition centers in a cell VC_i with respect to aircrafts' position and velocity in x direction of the coordinate axes. The partition center for position is expressed in meters. The partition center for velocity vector is expressed in m/sec.

Table 4.3: Partition of Node Position and Velocity in a Cell

Center	X Position Vector	X Velocity Vector
C1	7315.3288879168	206.4715298787
C2	2952.0141430816	342.9901238212
C3	13011.2889235821	-142.5390132334

The relative displacement between the position partition centers gives an idea regarding the spread of the network. This displacement also helps in identifying groups of nodes which are closely spaced to each other at any time instant. The maximum distance between two aircrafts to support an air-to-air links can reach up to 200 and 400nmi (roughly 371km to 742km). For our simulated scenario, it appears that the 3 groups of aircrafts under consideration have clear potential to establish AANET links amongst them. This can be used to decide whether a cross link between two sub-AANET is permissible or not. The HAP in the cell can observe the directional groups and inform each aircraft in the cell about its relative closeness to each directional group. This information is made available to the aircrafts in terms of the **status update**. The status update given to each aircraft by the HAP depends on the "proximity" of the aircrafts with respect to each partition center. The proximity of aircrafts to a partition center is decided by its "membership" to the respective partition center. The FCM clustering on the data vectors return membership values for each vector. The membership value is the measure of closeness or "association" a data vector to the centers. Thus, the proximity of an aircraft to a partition center is a measure of its association to a group. When an aircraft switches from one group to another, its proximity decreases with one group and increases with another. The position partition center gives and idea of separation between groups of aircrafts, and the velocity partition center gives idea regarding the direction of the motion. Also, the difference in the relative velocities between groups of aircrafts can be estimated. This information can be used by the aircrafts to identify aircrafts moving towards them or away from them.

Table 4.4 presents the membership values with respect to x position vector (Table 4.3) of an aircraft.

Table 4.4: Node Membership to Partitions

Center	Membership Value
C1	0.0539341779
C2	0.0762900907
C3	0.8697757314

It can be observed that the aircraft belongs to partition center C3, due to its highest membership to the center. Thus, if the motion of aircrafts are monitored along the x-axis, it may be inferred that at the particular time instant the aircrafts position is closer to 13 km. At the same time, the velocity vector suggests that the aircraft is headed in the opposite direction. The aircrafts which do not show any group behavior, i.e. the isolated aircrafts, can also be associated with the group mobility vectors. The membership value can clearly indicate how far they are from the group mobility vectors.

Another responsibility of the HAP is to identify the congestion classes in the cell. Concurrently, it has to relay this information to every aircraft. The congestion in each aircraft is received by the HAP through the registration message. As congestion is essentially packets queued in the aircrafts, to measure the congestion all queues in an aircraft should be considered. Every aircraft is a multi-queue system. A multi-queue system implies that, every active link is equivalent to a queue. The packet arrival rate at every queue may be modeled as a Poisson process. The packet arrival rate λ_p need not be same for every queue. In this scenario, "traffic" or congestion **Q** in an aircraft can be expressed as a sum of individual queue lengths L_i. The queue length is number of packets waiting to be delivered. Therefore, Q can be expressed as

$$Q = \sum_{i=1}^{M} L_i \tag{4.9}$$

Every queue is assumed to have infinite buffer capacity. The queuing delay in each of the multiple queue systems influence the number of packets waiting for transmission. To emulate this varying congestion level in the aircrafts, we assume that a random congestion level is infused in each aircraft to model the traffic in the network. This ensures that some aircrafts are heavily congested and others are not. The congestion in the aircrafts is varied in every second. Using FCM clustering, we divide the congestion in a cell into three classes of *high*, *low*, and *medium* traffic. The membership of an aircraft to each class gives the measure of its congestion level. An aircraft is highly congested if its membership value to the higher congestion class is greater than that of the others. Fig. 4.4 shows the variation of the congestion class in the cell observed over a period of 1000secs. The congestion class is expressed in number of packets waiting in the buffer at any time instance.

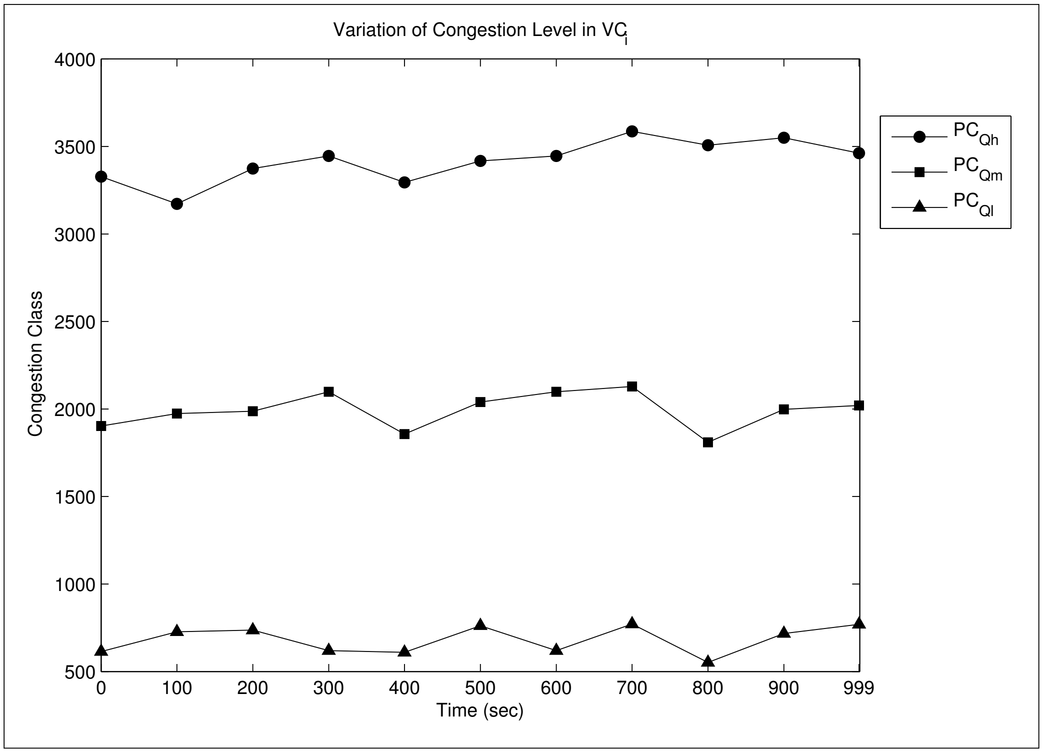

Figure 4.4: Congestion Class in Cell VC_i

The variation in the three congestion classes shows the level of traffic "hot spots" in the cell. The record of the membership value of every registered aircraft is maintained in the HAP. Therefore, if a group of aircrafts departs or enters a cell, the congestion classes are updated accordingly. Similarly, the partition centers for position and velocity data vectors are updated. The FCM clustering on aircrafts' data vector complement the dynamic nature of the AANET. This is because the change in the network parameters are reflected back to the aircrafts. This is a continuous process. This is achieved by encapsulating the network partition matrix in the status update received by the aircrafts.

HAP ID		
C1	C2	C3
U1	U2	U3
TIME STAMP		

Figure 4.5: Membership Message

The format of the status update message is depicted in Fig. 4.5. The status update message will contain the current network administrator's ID or the HAP ID. The time stamp is used by the aircrafts to track the most recent status using update from the HAP and update themselves accordingly. Since the status update message contain the current partition centers and the membership of each aircraft with respect to them, every aircraft is now aware of the changing network scenario. With this information the aircraft can identify its status with respect to other aircrafts in the cell without maintaining record about every aircraft in the network. When aircraft enters a new cell, the HAP ID is changed in the status update message. The aircraft now receives updates according to network scenario in the current cell.

4.2 Finding the Number of Mobility Groups and Congestion Classes

The aim of our monitoring scheme is to identify an aircrafts status with respect to other aircrafts in the cell. Since aircrafts status is measured with respect to its proximity to mobility groups and the congestion classes, the HAP should be able to identify the number of groups and classes in its cell. The partition of the velocity and position data vectors of aircrafts in a cell is equivalent to finding the number of mobility groups. The partitioning of the congestion values leads to the identification of congestions classes in the cell. The number of mobility groups in a spherical region S_r can be different. The question is how to find the exact number of directional groups and congestion level in each group as well as in the entire cell.

Fig. 4.6 is a 2D projection of velocity vectors plotted in Cartesian axes. The vectors represent the motion of aircrafts flying at different FL in the x-y plane. Our primary objective here, was to observe the accuracy of identification of the group mobility vectors. On FCM clustering the centers of the mobility groups are identified and marked as seen in the plots. Initially, with the number of clusters set to 3, three mobility groups are distinguished from each other in the mobility projection.

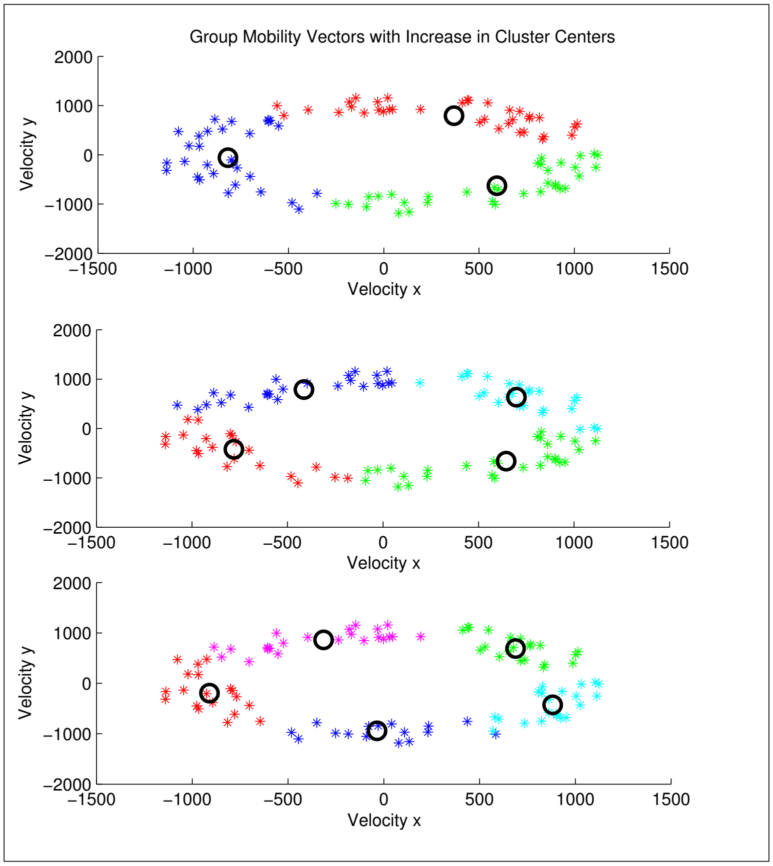

Figure 4.6: Group Mobility Vectors with Increasing Cluster Centers

In subsequent plots, the number of cluster centers is increased to 4 and 5. This helps in identifying an equivalent number of mobility groups respectively for the same mobility projection of the aircrafts. The group mobility vectors identified in all the three cases are widely spaced from each other, giving the impression that no merging of clusters is required. However, on careful observation it can be noted that, when number of clusters is increased, original cluster of data vectors are divided into new clusters. It can be seen that clusters which are not closely spaced, are correctly identified as a mobility group. But, clusters which do not have clear boundary separation are erroneously classified. Therefore, for closely spaced clusters (with no clear boundary separation), it can be concluded that data vectors at the edge of the clusters have higher chance of getting misclassified. Therefore, aircrafts radially farthest from the group mobility vectors, will be conspicuously identified if their radial distance from other group mobility vectors is same. Increasing the number of clusters creates extensive partitioning. With extensive partitioning, the cluster centers will eventually coincide with the data vector itself.

An extensive partition of the network in a cell, as demonstrated by Fig. 4.7, with respect to congestion in the network was done. The increase in number of cluster centers is plotted against the highest congestion class. The flat line indicates the actual number of packets queued in the aircraft. It is evident that with the increasing number of cluster centers, the value of highest congestion class tend to approach the actual congestion level in the aircraft. This observation can be extended with respect to position and velocity data vectors as well. It is indicative of the fact that with extensive partitioning of the data vectors of registered aircrafts in a cell, the HAP can closely monitor individual aircraft. However, monitoring of individual aircraft is not required, because the HAP maintains the record of aircrafts' data. Moreover, increasing the number of cluster centers implies the increase in size of the network partition matrix. The network partition matrix is reverted back to the aircrafts through the membership messages. Increasing the number of cluster centers would increase the size of status update messages or the membership messages. Hence, the number of mobility groups in S_r can be modeled as a complex

Poisson process, dependent on the aircraft density in the region, the arrival and departure rates of the aircrafts in the region. Given this, the HAP can decide on the exact number of mobility groups and congestion class for a registered number of aircrafts in the cell. Designing this decision making algorithm is one of the future extensions of our current research.

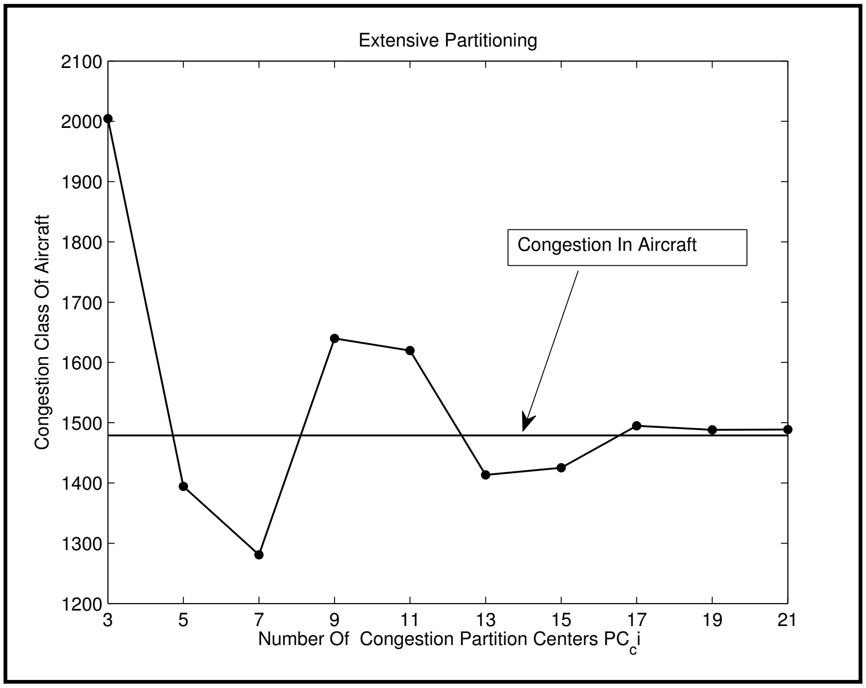

Figure 4.7: Extensive Network Partition

Section 4.3 presents our discussion on how the HAP uses the network partition matrix of the network to identify the directional group of aircrafts. The FCM clustering analysis of the registered aircrafts is used by HAP to predict connectivity in the cell, as observed by it in each spherical sector. We have assumed that exactly 3 mobility groups exist in every cell at every time instance. Also, the congestion classes have been categorized as high, low and medium.

4.3 Connectivity Prediction in a Cell

A cell can have varying aircraft density over a time period. The connectivity between two aircrafts or a group of aircrafts is primarily influenced by proximity of the aircrafts and congestion. Beyond the permissive LOS range of communication there is link breakage due to attenuation of signals. Hence, it is the HAPs responsibility to identify the group of aircrafts demonstrating a directional behaviour. The partition matrix of the network obtained by HAP can be used to identify the directional group of aircrafts. Since the congestion level in individual aircrafts decides its participation in the AANET, the number of sub AANET or clusters in the cell depends on the directional groups and the congestion level in the cell. In this section, we elaborate our analysis on identifying the directional behaviour and congestion in the network for making connectivity predictions using the network partition matrix. Table 4.5 lists the notations used in section 4.3.

Table 4.5: Notations and their Meanings

Symbols	Meaning
mg	Mobility Group
CL	Congestion Level
DM	Directional Mobility
C	Connectivity
n_{dm}	Number of Aircrafts showing Directional Mobility
n_c	Number of Congested Aircrafts
P_{DM}	Probability of Directional Mobility
P_{CL}	Probability of Congestion Level
P_C	Probability of Connectivity
N	Number of Aircrafts

4.3.1 Directional Mobility in a Cell

The "directional" behaviour of aircrafts in a spherical region S_r can be identified by estimating the number of closely spaced aircrafts in every mobility group. Let n_{dm} represent the number of aircrafts in a mobility group mg_i and in acceptable range of each other to form a network. n_{dm} can be considered as a discrete random variable. If all aircrafts populate the same mobility group, and are not dispersed far away from each other then, $mg_i = 1$ and $n_{dm} = N$. Given this, the "directional mobility" can be expressed as probability of n_{dm} aircrafts showing directional behaviour in a mobility group mg_i. $P_{DM_{mg_i}}$ can be found using Eqn. 4.10.

$$P_{DM_{mg_i}} = \frac{n_{dm_i}}{N_{mg_i}} \tag{4.10}$$

Thus, for a region S_r populated with more than one mobility group, the directional behaviour can be calculated using Eqn. 4.11.

$$P_{DM_r} = \frac{\sum_{i=1}^{mg} n_{dm_i}}{\sum_{i=1}^{mg} N_{mg_i}} \tag{4.11}$$

$\sum_{i=1}^{mg} n_{dm_i}$ gives the total number of aircrafts in proximity to each other for a given number of mobility groups. $\sum_{i=1}^{mg} N_{mg_i}$ gives the total number of aircrafts populating a region S_r for a given number of mobility groups in the the region. Fig. 4.8 shows a plot of the directional mobility, observed in the spherical regions over a period of 1000 seconds. A zero directional mobility implies the absence of mobility groups or any aircraft in the particular region. This is because, the FCM clustering ensures that every aircraft necessarily belongs to at least one mobility group (Eqn. 4.4). Hence, zero directional mobility can be used to identify the absence of aircrafts in a region. The directional mobility is 1 during majority of the observed time period. This signifies that aircrafts in the mobility groups are in required proximity to form a network. A directional mobility less than 1 implies that, aircrafts in the mobility groups are not in proximal range, but dispersed in the airspace. Since zero directional mobility implies the absence of mobility group in the region, it can be concluded that spherical region three has undergone more topology change than the other two regions. This is because the instance of zero directional mobility in the region are more as compared to other two regions.

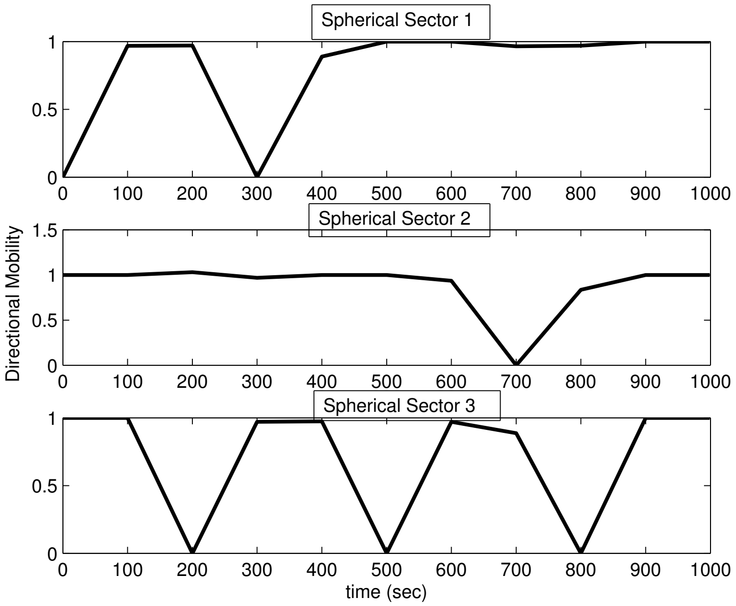

Figure 4.8: Directional Mobility in Spherical Sectors

4.3.2 Congestion in a Cell

On a given time instant, the aircrafts belonging to the *high* congestion class are highly congested. Therefore, for a given number of aircrafts, the probability of n_c aircrafts being congested can be found using Eqn. 4.12, where n_c is the number of aircrafts belonging to the highest congestion class and N is the total number of aircrafts in the cell.

$$P_{congestion} = \frac{n_c}{N} \tag{4.12}$$

Fig. 4.9 depicts the variation of congestion level in the cell observed over a time period of 1000 seconds. Within the observed time window, the maximum congestion in the cell occurs when 45 percent of the aircrafts in the cell belong to the highest congestion class. It is also observed that the congestion in the cell is time variant.

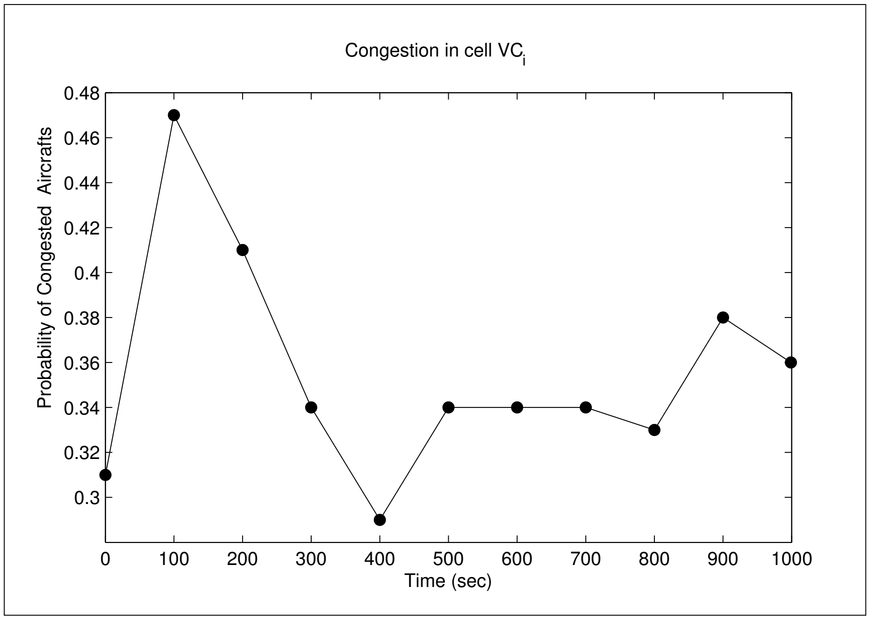

Figure 4.9: Congestion Class in Cell VC_i

Similarly, n_c represents the number of highly congested aircrafts in a mobility group mg_i. Thus, n_c can be considered as a discrete random variable. Given this, the "congestion level" CL can be expressed as a probability of n_c aircrafts in a mobility group mg_i, being congested. Thus, $P_{CL_{mg_i}}$ can be found using Eqn. 4.13.

$$P_{CL_{mg_i}} = \frac{n_{ci}}{N_{mg_i}} \tag{4.13}$$

For **mg** > 1, in region S_r the congestion level is found using Eqn. 4.14

$$P_{CL_{mg}} = \frac{\sum_{i=1}^{mg} n_{ci}}{\sum_{i=1}^{mg} N_{mg_i}} \tag{4.14}$$

where $\sum_{i=1}^{mg} n_{ci}$ represents the total number of congested aircrafts and $\sum_{i=1}^{mg} N_{mg_i}$ represents the total number of aircrafts populating a regionS_r. Fig. 4.10 shows a plot of congestion level in the network monitored over a period of 1000 seconds. The congestion level as seen by the HAP H_i in cell VC_i is plotted for each spherical sector. Since FCM clustering is used for deciding congestion classes, every aircraft in the cell VC_i necessarily belongs to a congestion class (Eqn. 4.4). Hence, a zero congestion level indicates the absence of aircrafts or any mobility group in the region at the particular time instance.

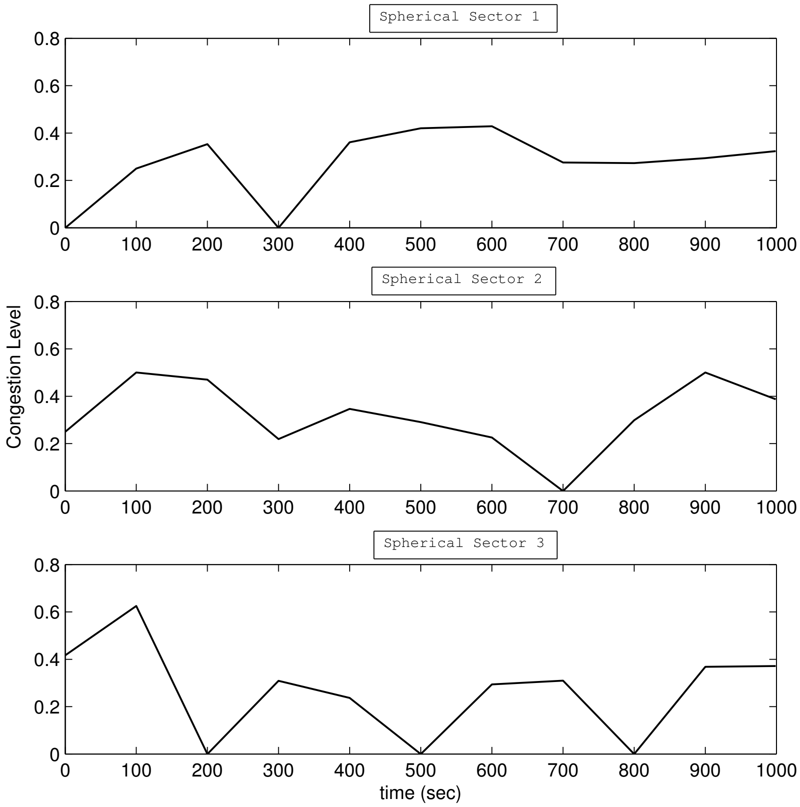

Figure 4.10: Congestion Level in Spherical Sectors

4.3.3 Connectivity in a Cell

The connectivity C in any region S_r of the airspace can be expressed as a function of directional mobility DM (Eqn. 4.10) and congestion level CL (Eqn. 4.14). That is, $C = f(DM, CL)$. The connectivity in a group of aircrafts showing high directional behaviour depends on the congestion level in the group. The HAP has to identify the number of congested aircrafts in a mobility group showing directional behaviour for making connectivity prediction. The aircrafts which can form a network can be represented using Fig. 4.11. The directional behavior is shown by aircrafts belonging to the innermost circle.

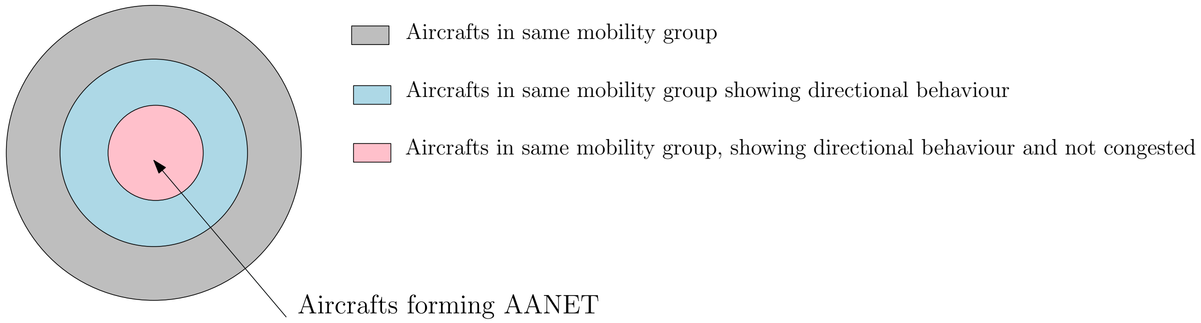

Figure 4.11: Directional Behaviour

Therefore, the HAP needs to find the probability of aircrafts not being congested. The probability of aircrafts not being congested in each mobility group can obtained using Eqn. 4.15, where $P_{CL_{mg_i}}$ is the congestion level in respective mobility groups.

$$P_{NCL_{mg_i}} = (1 - P_{CL_{mg_i}}) \tag{4.15}$$

The connectivity in each mobility group can be expressed using Eqn. 4.16. $P_{DM_{mg_i}}$ and $(1 - P_{CL_{mg_i}})$ represent the directional mobility and the non-congested aircrafts in the mobility group, respectively.

$$P_{C_{mg_i}} = P_{DM_{mg_i}} \times (1 - P_{CL_{mg_i}}) \tag{4.16}$$

When region S_r is populated with more than one mobility group, the connectivity in the region can be found using Eqn. 4.17. Here, n_{dm_i} is the number of aircrafts showing directional behaviour in a mobility group. n_{ci} represents the number of directionally mobile congested aircrafts in the mobility group. The total number of aircrafts populating the region can be obtained as the sum of aircrafts in each mobility group using $\sum_{i=1}^{mg} N_{mg_i}$.

$$P_{C_r} = \frac{\sum_{i=1}^{mg} n_{dm_i}}{\sum_{i=1}^{mg} N_{mg_i}} \times \left(1 - \left(\frac{\sum_{i=1}^{mg} n_{ci}}{\sum_{i=1}^{mg} N_{mg_i}}\right)\right) \tag{4.17}$$

4.3.4 Ideal Connectivity Surface

A spherical region S_r in the cell may be populated with varying densities of aircrafts. Since the number of distinct mobility groups of aircrafts in the region is time variant, the connectivity of the network changes with topology change. Eqn. 4.16 generates an ideal connectivity surface (Fig 4.12). The connectivity of the network at every time instance can be mapped on to this surface. A group of aircrafts showing high directional behaviour will have less connectivity if the congestion level is high. Thus, over a time period **T** if connectivity points lie towards upper area of the surface, intuitively it can be said that an AANET between the aircrafts will be sustained for a longer duration. The four corner points on the surface can be used to make the following predictions regarding the connectivity of the AANET formed by a group of aircrafts or sub-AANETs.

- Zero connectivity represented by zero directional mobility and congestion level indicates the absence of mobility groups or any aircraft in the region.

- A connectivity value of one represented by directional mobility of value one and the congestion level zero. It implies that the aircrafts in the proximity are not participating in the AANET. These aircrafts may be in ideal state as depicted in Fig. 3.1 (Chapter 3). During this time, new AANET links can be easily established.

- A zero connectivity represented by directional mobility of value one and congestion level one. This indicates that all the aircrafts in the region are highly congested.

Intuitively, it can be concluded that the sustainability of the AANET will be low in the region.

- A zero connectivity represented by directional mobility of value zero and congestion level one. This represents the situation where aircrafts in a mobility group are dispersed from each other such that no AANET link can be established between the sub-AANETs. At the same time, the congestion level of one indicates that aircrafts in the sub-AANETs are highly congested.

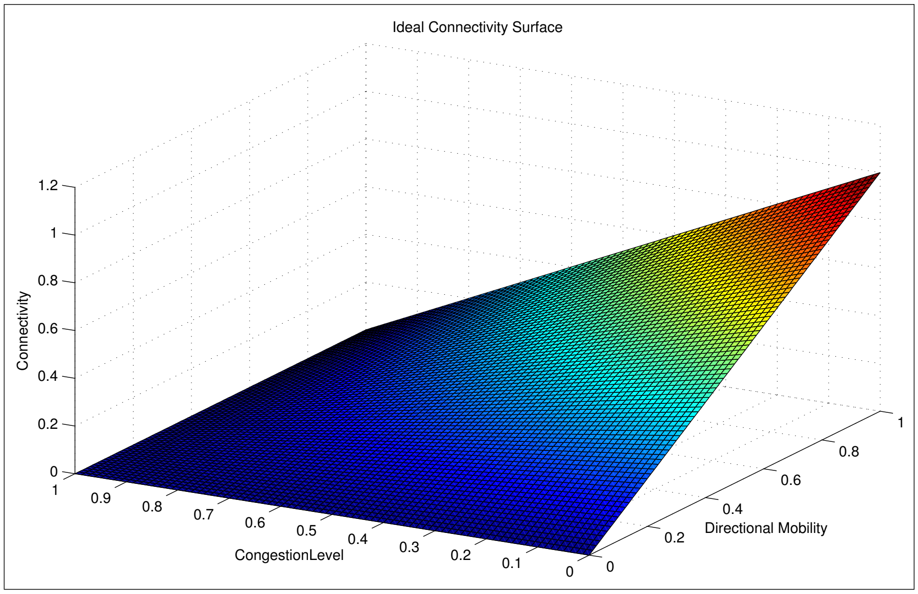

Figure 4.12: Ideal Connectivity Surface

For a given time period $\mathbf{T}$ and a region S_r, if the connectivity mapping on the ideal surface fluctuates very often, then it is evident that the sustainability of the AANET in the region is low. For a stable network in the region, the connectivity mapping at every time instant should be same or show minimum amount of variation.

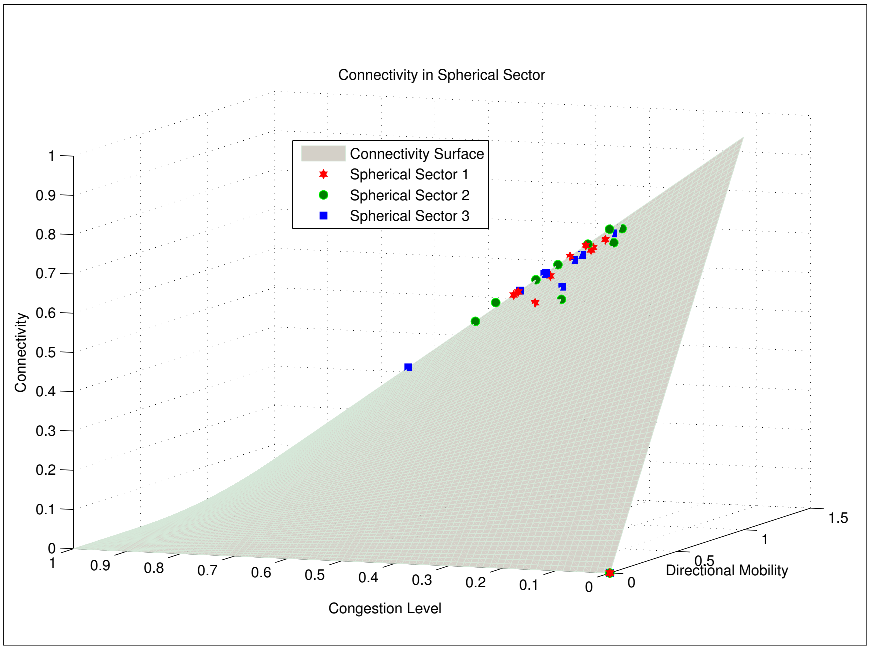

Figure 4.13: Connectivity in Spherical Sectors

Fig. 4.13 shows the connectivity plot of the spherical regions obtained from our simulation. We map the connectivity of the three spherical regions on the connectivity surface. For majority of the time period the connectivity in the regions are limited to 80 percent. This is because the congestion level in the mobility groups limit the connectivity. There are some points showing zero connectivity, implying the drift of mobility groups from one region to another in the cell. We observe that the variation in the connectivity of third spherical region (denoted by blue markers) is more than the first and second regions in the cell. This is mainly due to the frequent variation of directional mobility (Fig. 4.8) and the congestion level (Fig. 4.10) in the region. This suggests that during the observed time period spherical region three of the cell underwent more topology change as compared to the other two regions (due to frequent change in number of mobility groups in the region).

Section 4.4 presents a brief discussion on routing strategy that can be realized using our network model.

4.4 Routing Strategy

The Voronoi space tessellation creates a cellular service architecture in the airspace. Fig. 4.14 represents the tessellated airspace. A possible arrangement of aircrafts is also depicted. Such mixed topology of clusters and mesh of aircrafts can exist within a cell, or, it can be spread across many cells. A cluster of aircrafts can be connected to a mesh of aircrafts, as seen from connection between aircraft 2 and aircraft 5, where aircraft 2 can be a cluster head. The disconnectivity that might occur due to topology change is depicted using the dashed lines.

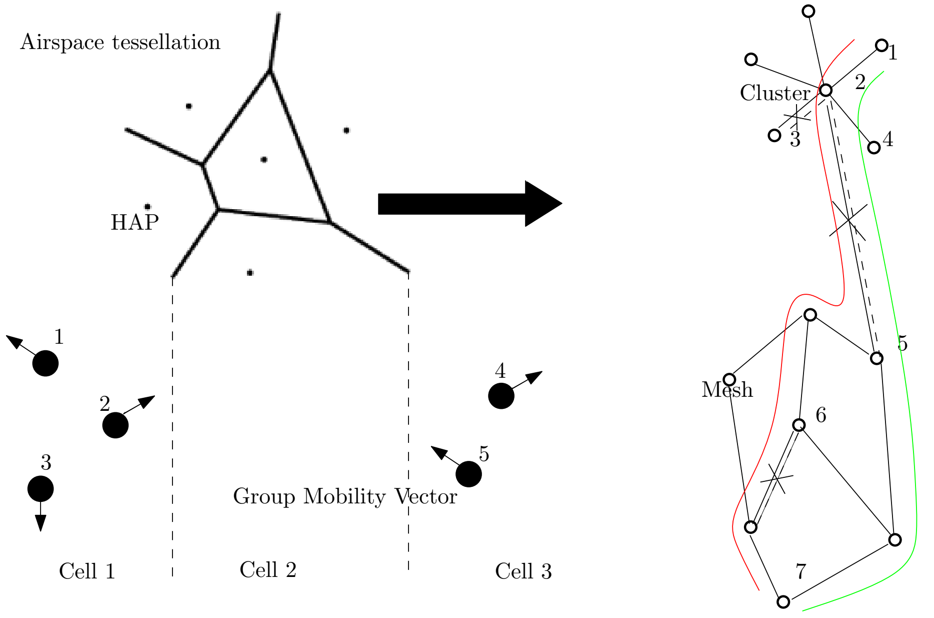

Figure 4.14: Network Topology

Aircraft Address: As an aircraft moves from one cell to another, their should be no conflict in the address of data packets originating from the aircraft. That is, the address should be dynamically configured with aircrafts' motion. Therefore, in event of inter-cell routing (source and destination aircrafts in the same cell) or intra-cell routing (source and destination aircrafts are in different cells), the identification of address should be consistent. Thus, aircrafts should dynamically configure their address as they move from one cell to other. The unique addresses can be obtained by clubbing the 24 bit identifier address of each aircraft with the HAP ID. Thus, when an aircraft changes its cell, the HAP ID will change, generating unique address.

Neighbor Discovery: An aircraft can discover its neighbors by listening to "Hello" messages. Therefore, the neighbor table of each aircraft can be populated. A hello message is issued with the latest network partition matrix of each aircraft and a flag status, indicating an aircraft's membership to a cluster or mesh.

Disconnectivity: An aircraft is disconnected if it cannot establish a link to a cluster of aircrafts or a mesh of aircrafts. The connectivity analysis shows that our network monitoring scheme can predict the connectivity regions in the AANET. When an aircraft gets disconnected, it can request the HAP for network information. The HAP should direct the aircraft to regions of high connectivity. On receiving network information from the HAP, an aircraft broadcasts a "Join Request" containing its network partition matrix. A neighbor aircraft receiving join requests from more than one aircraft at a time can "accept" all the requests or accept some of them. This can be decided by comparing its network partition matrix with that of an aircraft sending join request. The probability of getting accepted will be high if, both the aircrafts are in same mobility group and in same congestion class, or if the congestion threshold of aircraft receiving join requests is lesser than that of aircraft sending join request. Aircrafts joining a cluster with a mesh, form the gateway nodes in the network.

Fig. 4.15 outlines the event of disconnectivity in the AANET.

Routing: For any source-destination pair of aircrafts, the routing begins with the broadcasting of Route Request (RREQ) request by source aircraft. The latest network partition matrix of source aircraft is included in the RREQ. The network partition matrix

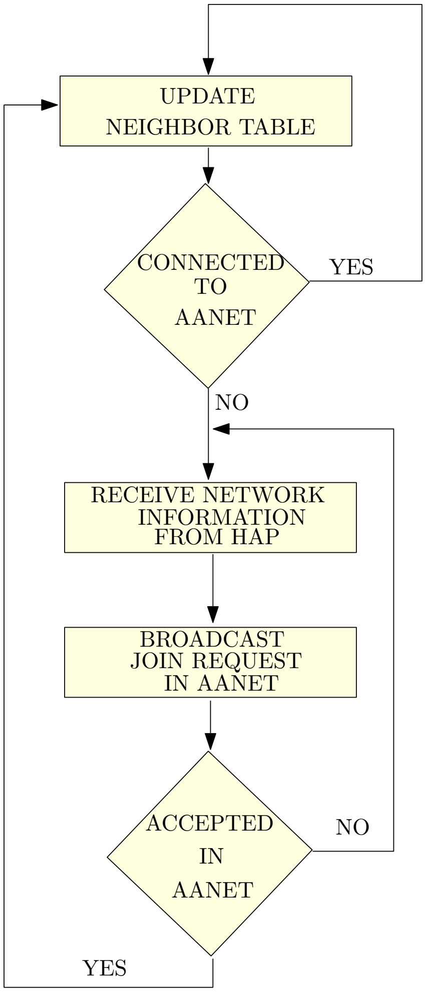

Figure 4.15: Aircraft Disconnectivity

is the essence of our class based routing. When a RREQ is issued, a source aircraft can set a priority for routing of the packets. That is, it can select aircraft position, velocity or congestion as a means to identify the next relay aircraft or the intermediate aircraft. Giving priority to the routing according to a property, makes the routing multi-objective. The routing can be prioritized in three ways: (1) packets can be progressively forwarded to aircrafts moving in same direction, (2) packets can be forwarded to aircrafts flying with less difference in relative velocities, and (3) packets can be forwarded along the least congested path (the latter can be coupled with other two former modes of routing).

For example, if aircraft 1 wants to reach aircraft 7, it sets the priority of route selection. First, the neighbor table is searched for the destination aircraft. If destination aircraft exists in the one hop neighborhood then an immediate RREQ is sent to the aircraft. The destination aircraft should respond with a Route Reply (RREP) message. If destination aircraft is not found in the one hop neighborhood but exists in range, then RREQ is broadcasted to those aircrafts which are moving in the direction of the destination. This can be done by choosing aircrafts which are in the same mobility groups as that of aircraft. The closeness of the aircrafts to the required group mobility vector can be estimated from their membership values. Therefore, mobility is the primary objective here. When destination aircraft is not found in neighbor table at all, the RREQ is broadcasted to the aircrafts positioned closer to the aircrafts issuing the RREQ. This way, RREQ is forwarded until destination aircraft is discovered in the neighborhood. Here, position of the aircrafts is given higher priority. Every time a RREQ is forwarded, the previous network partition matrix is replaced by the network partition matrix of the forwarding aircraft. This ensures that receiver knows about the status of the sender. Also, when route is spread across different cells, the network scenario of the new cell is immediately encapsulated in the RREQ. A cost is added to the RREQ packet each time is forwarded. When destination aircraft finally receives a forwarded RREQ, a RREP is unicasted back. If RREQ messages are forwarded via multiple paths (e.g. path marked green and path marked red), the path with least cost is chosen. The cost function can be modeled as a function of association with the position partition centers, group mobility vectors and congestion thresholds. The cost function is expected to inform the destination aircraft regarding spread of the route and the congestion along the path. A timeout parameter can help in detecting route failures. The timeout should be tracked by the source aircraft, if a route is not established within the permissible timeout range, it is indicative of the fact that destination aircraft could not be reached. We anticipate that inclusion of local network information in the routing of packets will produce less local maximas during packet forwarding. Also, in case maximas occur the priority routing can help in mitigate the delay of finding the relay aircrafts, by switching the priority between the multiple objectives. The routing is essentially a hybrid of reactive and proactive routing schemes. This is because inspite of being table driven, end to end routes are not maintained in the aircrafts. The neighbor table are dynamically built depending upon the "listening" range of each aircraft. Although, the route discovery phase appears to emulate basic AODV and GPSR routing schemes, the criteria for identifying intermediate nodes along the route makes our strategy different. Our routing strategy is not a position based scheme. It is an association based strategy, where class based association of aircrafts to the group mobility vectors and congestion thresholds governs the route discovery process.

4.5 Summary

In this chapter, we have examined how FCM clustering can be used for monitoring 3-dimensional AANET. The FCM clustering is used by the network administrator (HAP) for monitoring the network activity. The class based maintenance of network status helps in identifying every aircrafts status globally in a cell. The network partition matrix obtained using FCM clustering is used to generate the status updates for the aircrafts in the cell. The connectivity in the cell can be observed by the HAP. This priori knowledge of the network proves useful in the event of disconnectivity. A disconnected aircraft from the network can retrieve information regarding higher connectivity regions in the cell, reducing its period of disconnectivity from the AANET. The network partition matrix can also be used for making routing decisions. Table 4.6 summarizes our connectivity analysis in a cell in terms of directional mobility, congestion level and stability of the AANET.

Table 4.6: Connectivity Prediction in Cell

Case	Directional Mobility	Congestion Level	Connectivity	Change in Connectivity	Stability
1.	Low	Low	Low	Low	High
2.	Low	High	Low	Low	High
3.	High	Low	High	Low	High
4.	High	High	Low	Low	High
5.	Low	Low	Low	High	Low
6.	Low	High	Low	High	Low
7.	High	Low	High	High	Low
8.	High	High	Low	High	Low

Therefore, case 3 seems to be the most preferable condition for forming an AANET.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this research, we proposed a network monitoring scheme for AANET using a quasi stationary layer of HAPs in the airspace. We also proposed the use of FCM data clustering for tracking network changes in AANET. The following can be concluded regarding network monitoring of AANET using quasi stationary HAP layer in the airspace.

1. The quasi stationary layer of HAPs using Voronoi space tessellation provides a stable monitoring structure in the airspace. Such a structure can be realized to cover the airspace over both, terrestrial masses and oceanic surfaces through strategic placements of the HAPs.

2. As a monitoring agent or network administrator, the HAPs can observe the network in terms of connectivity. It can identify the traffic hot spots. This knowledge is useful for identifying events of router displacement and disconnectivity. At the same time, disconnected routers can be connected to the network again without much delay, restoring the connectivity of the AANET.

3. The quasi stationary layer of HAP creates a cellular service architecture in the airspace. This can be used to develop a MANET-IP centric architecture for the

AANET, so that end-to-end paths between aircrafts can be maintained across the airspace. Such architecture can be useful for transferring voice, data and multimedia traffic across the AANET.

The FCM clustering is an integral part of our monitoring scheme. The following can be concluded about the FCM clustering for network monitoring in AANET.

1. FCM complements the dynamic nature of the AANET. It helps in translating the physical geometry of the network into relevant network statistics in the HAP's database. This makes our monitoring system intelligent.

2. It is understood that the connectivity in the AANET is uneven and subjective to topology changes. The "clustering" helps in tracking the network partitions, by tracking the group mobility vectors and congestion classes in the cells. Given this the "directional behaviour", the "congestion level" can be identified. Therefore, FCM data clustering can help in monitoring the uneven connectivity of the network.

3. The "ideal connectivity" surface obtained from our mathematical analysis demonstrates that FCM clustering accounts the connectivity of the network irrespective of an aircraft's state (idle, mesh, clustered and migrating). The soft clustering not only keeps track of group switches of the aircrafts, it also associates every aircraft to a group mobility vector and congestion class. This helps in keeping track of isolated aircrafts in the network.

4. The network partition matrix, encapsulated in the "membership messages", helps an aircraft identify itself with the current network status. Therefore, an aircraft has to depend only on the HAP in a cell to obtain network information. This reduces the flooding of network with join request messages in events of disconnectivity. Also, aircrafts are not overloaded with frequent topology updates from neighboring aircrafts, since they are "aware" of the network scenario.

5.2 Future Work

We now list some possible extensions to our work.

- FCM data clustering effectively associates the aircrafts with partition centers (group mobility vectors and congestion thresholds), by assigning membership to them. This tracks the directional behavior and congestion classes in the network. Identifying the exact number of partition centers in a cell is imperative. But, for incorporating FCM clustering, the number of clusters should be known to the HAP. This is a drawback for our monitoring scheme. Because the number mobility groups and congestion class are not constant, the latest number of partition centers should be available to the HAP, and only then FCM analysis can be done. Designing an algorithm for this purpose can be considered in future. The decision making algorithm can be modeled as a complex Poisson process, dependent on the aircraft density in the region, arrival and departure rates of the aircrafts in the region.
- Design and implementation of a multi-objective routing protocol based on the proposed routing strategy that can be implemented in the network layer for the AANET.

Bibliography

[1] "`http://www.flightradar24.com`".

[2] "`http://cordis.europa.eu/projects/502843`".

[3] Ariyakhajorn, J., Wannawilai, P., and Sathitwiriyawong, C., "A Comparative Study of Random Waypoint and Gauss-Markov Mobility Models in the Performance Evaluation of MANET", Proc. of *International Symposium on Communications and Information Technologies*, pp. 894–899, 2006.

[4] Ayaz, S., Bauer, C., Eddy, W. M., and Arnal, F., "Nemo Route Optimization Solution Space Analysis and Evaluation Criteria for Aviation", Proc. of *8th International Conference on ITS Telecommunications*, pp. 139–145, 2008.

[5] Basu, P., Khan, N., and Little, T. D., "A Mobility Based Metric for Clustering in Mobile Ad Hoc Networks", Proc. of *IEEE International Conference on Distributed Computing Systems Workshop*, pp. 413–418, 2001.

[6] Bekmezci, İ., Sahingoz, O. K., and Temel, Ş., "Flying Ad-Hoc Networks (FANETs): A Survey", *Ad Hoc Networks*, **11**, 1254–1270, 2013.

[7] Ben Mahmoud, M. and Larrieu, N., "An ADS-B Based Secure Geographical Routing Protocol for Aeronautical Ad Hoc Networks", Proc. of *IEEE 37th Annual Computer Software and Applications Conference Workshops (COMPSACW)*, pp. 556–562, 2013.

[8] Besse, F., Garcia, F., Pirovano, A., and Radzik, J., "Wireless Ad Hoc Networks Access for Aeronautical Communications", Proc. of *28th AIAA International Communications Satellite Systems Conference*, pp. 1-15, 2010.

[9] Besse, F., Pirovano, A., Garcia, F., and Radzik, J., "Interference Estimation in an Aeronautical Ad Hoc Network", Proc. of *IEEE/AIAA 30th Digital Avionics Systems Conference (DASC)*, pp. 4C6–1–4C6–11, 2011.

[10] Bezdek, J. C., Ehrlich, R., and Full, W., "FCM: The Fuzzy C Means Clustering Algorithm", *Computers & Geosciences*, **10**, 191–203, 1984.

[11] Bretmersky, S., Konangi, V. K., and Kerczewski, R. J., "Comparison of VDL Modes in the Aeronautical Telecommunications Network", Proc. of *IEEE Aerospace Conference*, vol. 3, pp.1183-1183, 2002.

[12] Brooker, P., "Sesar and Nextgen: Investing in New Paradigms", *Journal of navigation*, **61**, 195–208, 2008.

[13] Broyles, D., Jabbar, A., and Sterbenz, J. P., "Design and Analysis of a 3-D Gauss-Markov Mobility Model for Highly Dynamic Airborne Networks", Proc. of *International Telemetering Conference (ITC)*, 2010.

[14] C. Perkins, E. B.-R. and Das, S., "Ad hoc On-demand Distance Vector (AODV) routing", *RFC 3561 (Experimental)*, 2003.

[15] Camp, T., Boleng, J., and Davies, V., "A Survey of Mobility Models for Ad Hoc Network Research", *Wireless Communications and Mobile Computing*, **2**, 483–502, 2002.

[16] Chen, B.-S., Peng, S.-C., and Wang, K.-C., "Traffic Modeling, Prediction, and Congestion Control for High-Speed Networks: A Fuzzy AR Approach", *IEEE Transactions on Fuzzy Systems*, **8**, 491–508, 2000.

[17] Colella, M., Martin, J., and Akyildiz, I., “The HALO Network”, *IEEE Communications Magazine*, **38**, 142–148, 2000.

[18] Cong-jun, S., Qing-hua, R., Bo, Z., and Yun-jiang, L., “Analysis of Node Density and Probability of Forming a Network in Military Aeronautical Ad Hoc Networks”, Proc. of *International Conference on Microwave and Millimeter Wave Technology*, vol. 4, pp. 1980–1982, 2008.

[19] Di Fatta, G., Hoffmann, F., Lo Re, G., and Urso, A., “A Genetic Algorithm for the Design of a Fuzzy Controller for Active Queue Management”, *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, **33**, 313–324, 2003.

[20] Eddy, W., Davis, T., and Ivancic, W., “Network Mobility Route Optimization Requirements for Operational use in Aeronautics and Space Exploration Mobile Networks”, *Network Working Group RFC 5522*, 2009.

[21] Franzen, N., “Comparison of Coordinated and Uncoordinated PHY/MAC Schemes for Beaconing”, Proc. of *IEEE/AIAA 31st Digital Avionics Systems Conference (DASC)*, pp. 5D1–1–5D1–12, 2012.

[22] Fuchs, C., et. al., “Broadband Communications for Aeronautical Networks: The Atenaa Outer Optical Link Validation”, Proc. of *1st CEAS European Air and Space Conference*, 2007.

[23] Gu, W., Li, J., Lv, M., Sun, Q., and Yang, F., “Delay Aware Multipath Doppler Routing in Aeronautical Ad Hoc Networks”, Proc. of *IEEE 14th International Conference on Computational Science and Engineering (CSE)*, pp. 251-255, 2011.

[24] Gu, W., Li, J., Zhang, H., Sun, Q., and Yang, F., “A Cluster-based Hybrid Routing Protocol for Aeronautical Ad hoc Networks”, *International Journal of Advancements in Computing Technology*, 2012.

[25] Hoffmann, F., Medina, D., and Wolisz, A., "Two-Step Delay Based Internet Gateway Selection Scheme for Aeronautical Ad Hoc Networks", Proc. of *Personal, 20th IEEE International Symposium on Indoor and Mobile Radio Communications*, pp. 2638–2642, 2009.

[26] Hoffmann, F., Medina, D., and Wolisz, A., "Optimization of Routing and Gateway Allocation in Aeronautical Ad Hoc Networks using Genetic Algorithms", Proc. of *7th International Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 1391–1396, 2011.

[27] Hoffmann, F., Medina, D., and Wolisz, A., "Joint Routing and Scheduling in Mobile Aeronautical Ad Hoc Networks", *IEEE Transactions on Vehicular Technology*, **62**, 2700–2712, 2013.

[28] Hyeon, S., Kim, K.-I., and Yang, S., "A New Geographic Routing Protocol for Aircraft Ad Hoc Networks", Proc. of *IEEE/AIAA 29th Digital Avionics Systems Conference/*, pp. 2.E.2–1–2.E.2–8, 2010.

[29] Iordanakis, M., Yannis, D., Karras, K., Bogdos, G., Dilintas, G., Amirfeiz, M., Colangelo, G., and Baiotti, S., "Ad-Hoc Routing Protocol for Aeronautical Mobile Ad-Hoc Networks", Proc. of *5th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, 2006.

[30] Jamalipour, A. and Sakhaee, E., "Aeronautical Ad-Hoc Networks", US Patent App. 12/094,535, 2009.

[31] Jardosh, A., Belding-Royer, E. M., Almeroth, K. C., and Suri, S., "Towards Realistic Mobility Models for Mobile Ad Hoc Networks", Proc. of *9th Annual International Conference on Mobile Computing and Networking*, pp. 217–229, 2003.

[32] Jones, W. H. and de La Chapelle, M., “Connexion by Boeing: Broadband Satellite Communication System for Mobile Platforms”, Proc. of *IEEE Military Communications Conference (MILCOM)* , vol. 2, pp. 755–758, 2001.

[33] Kanoh, H., Furukawa, T., Tsukahara, S., Hara, K., Nishi, H., and Kurokawa, H., “Short-Term Traffic Prediction using Fuzzy C-Means and Cellular Automata in a Wide-Area Road Network”, Proc. of *IEEE Intelligent Transportation Systems*, pp. 381–385, 2005.

[34] Karp, B. and Kung, H.-T., “GPSR: Greedy Perimeter Stateless Routing for Wireless Networks”, Proc. of *6th Annual International Conference on Mobile Computing and Networking*, pp. 243–254, 2000.

[35] Laase, E. and Richards, W. R.,“ Connexion by Boeing: A Satellite Solution for In-Flight Aircraft”, Proc. of *22nd AIAA International Communications Satellite Systems Conference & Exhibit*, 2004.

[36] Li, H., Yang, B., Chen, C., and Guan, X., “Connectivity of Aeronautical Ad Hoc Networks”, Proc. of *IEEE GLOBECOM Workshops* , pp. 1788–1792, 2010.

[37] Li, J., Gong, E., Sun, Z., Li, L., and Xie, H., “An interference-based distributed tdma scheduling algorithm for aeronautical ad hoc networks”, Proc. of *International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery*, pp. 453–460, 2013.

[38] Li, J., Lei, L., Liu, W., Shen, Y., and Zhu, G., “An Improved Semi-Markov Smooth Mobility Model for Aeronautical Ad Hoc Networks”, Proc. of *8th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM)*, pp. 1–4, 2012.

[39] Lin, C. R. and Gerla, M.,“ Adaptive Clustering for Mobile Wireless Networks”, *IEEE Journal on Selected Areas in Communications*, **15**, 1265–1275, 1997.

[40] Liu, D. and Lung, C.-H., "P2P Traffic Identification and Optimization using Fuzzy C-Means Clustering", Proc. of *IEEE International Conference on Fuzzy Systems (FUZZ)*, pp. 2245–2252, 2011.

[41] Marwaha, S., Srinivasan, D., Tham, C. K., and Vasilakos, A., "Evolutionary Fuzzy Multi-Objective Routing for Wireless Mobile Ad Hoc Networks", Proc. of *Congress on Evolutionary Computation*, vol. 2, pp. 1964–1971, 2004.

[42] Medina, D., Hoffmann, F., Ayaz, S., and Rokitansky, C.-H., "Feasibility of an Aeronautical Mobile Ad Hoc Network over the North Atlantic Corridor", Proc. of *5th Annual Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, pp. 109–116. 2008.

[43] Medina, D., Hoffmann, F., Ayaz, S., and Rokitansky, C.-H., "Topology Characterization of High Density Airspace Aeronautical Ad Hoc Networks", Proc. of *5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems*, pp. 295–304, 2008.

[44] Medina, D., Hoffmann, F., Rossetto, F., and Rokitansky, C.-H., "A Crosslayer Geographic Routing Algorithm for the Airborne Internet", Proc. of *IEEE International Conference on Communications (ICC)*, pp. 1–6, 2010.

[45] Miura, R., Maruyama, M., Suzuki, M., Tsuji, H., Oodo, M., and Nishi, Y., "Experiment of Telecom/Broadcasting Mission using a High-Altitude Solar-Powered Aerial Vehicle Pathfinder Plus", Proc. of *5th International Symposium on Wireless Personal Multimedia Communications*, vol. 2, pp. 469–473, 2002.

[46] Moazzami, F., Dean, R., and Astatke, Y., "Use of K-Means Clustering for Spectrum Efficiency in Complex Networks", Proc. of *47th Annual Conference on Information Sciences and Systems (CISS)*, pp. 1–3, 2013.

[47] My, N. T. X., Miyanaga, Y., and Saivichit, C., "Connectivity Analytical Modelling for a Single Flight Path Ad Hoc Aeronautical Network", Proc. of *International Con-*

ference on Electrical Engineering/Electronics Computer Telecommunications and Information Technology, pp. 51-55, 2010.

[48] Nyirenda, C. N. and Dawoud, D. S., "Multi-Objective Particle Swarm Optimization for Fuzzy Logic Based Active Queue Management", Proc. of *IEEE International Conference on Fuzzy Systems*, pp. 2231–2238, 2006.

[49] Ogier, R., Templin, F., and Lewis, M., "Topology Dissemination Based on Reverse-Path Forwarding (TBRPF)", *IETF, RFC 3684*, 2004.

[50] Oishi, R. T., "Future Applications and the Aeronautical Telecommunication Network", Proc. of *IEEE Aerospace Conference*, vol. 3, pp. 1333–1339, 2001.

[51] Palat, R., Annamalau, A., and Reed, J., "Cooperative Relaying for Ad-Hoc Ground Networks using Swarm UAVs", Proc. of *IEEE Military Communications Conference*, pp. 1588–1594, 2005.

[52] Peters, K., Jabbar, A., Cetinkaya, E., and Sterbenz, J., "A Geographical Routing Protocol for Highly-Dynamic Aeronautical Networks", Proc. of *Wireless Communications and Networking Conference (WCNC)*, pp. 492–497, 2011.

[53] Pisaruck, M., McLain, C., Kumar, A., and Yamanaka, O., "Connexion by Boeing: Broadband Satellite Services for Aircraft", *IEIC Technical Report (Institute of Electronics, Information and Communication Engineers)*, **102**, 105–109, 2002.

[54] Plass, S., "Seamless Networking for Aeronautical Communications: One Major Aspect of the SANDRA Concept", *IEEE Aerospace and Electronic Systems Magazine*, **27**, 21–27, 2012.

[55] Sakhaee, E. and Jamalipour, A., "The Global In-Flight Internet", *IEEE Journal on Selected Areas in Communications*, **24**, 1748–1757, 2006.

[56] Sakhaee, E. and Jamalipour, A., “Stable Clustering and Communications in Pseudolinear Highly Mobile Ad Hoc Networks”, *IEEE Transactions on Vehicular Technology*, **57**, 3769–3777, 2008.

[57] Sakhaee, E., Jamalipour, A., and Kato, N., “Aeronautical Ad Hoc Networks”, Proc. of *IEEE Wireless Communications and Networking Conference*, pp. 246–251, 2006.

[58] Sakhaee, E., Jamalipour, A., and Kato, N., “Multipath Doppler Routing with QOS Support in Pseudo-Linear Highly Mobile Ad Hoc Networks”, Proc. of *IEEE International Conference on Communications*, pp. 3566–3571, 2006.

[59] Sampigethaya, K., Poovendran, R., Shetty, S., Davis, T., and Royalty, C., “Future E-enabled Aircraft Communications and Security: The Next 20 Years and Beyond”, *Proceedings of the IEEE*, **99**, 2040–2055, 2011.

[60] Schnell, M. and Scalise, S., “Newsky-Concept for Networking the Sky for Civil Aeronautical Communications”, *IEEE Aerospace and Electronic Systems Magazine*, **22**, 25–29, 2007.

[61] Seo, D.-W., Kim, S.-H., and Suh, Y.-J., “System Integration of GPSR and ADS-B for Aeronautical Ad Hoc Networks”, Proc. of *IEEE Military Communications Conference*, pp. 1–6, 2008.

[62] Shirani, R., St-Hilaire, M., and Kunz, T., “A Cross-Layered Communication Architecture for Search and Surveillance Applications of Unmanned Aeronautical Ad-Hoc Networks”, Proc. of *8th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM)*, pp. 1–5, 2012.

[63] Shirani, R., St-Hilaire, M., Kunz, T., Zhou, Y., Li, J., and Lamont, L., “The Performance of Greedy Geographic Forwarding in Unmanned Aeronautical Ad-Hoc Networks”, Proc. of *9th Annual Communication Networks and Services Research Conference(CNSR)*, pp. 161–166, 2011.

[64] Thornton, J., Grace, D., Spillard, C., Konefal, T., and Tozer, T., “Broadband Communications from a High-Altitude Platform: The European Helinet Programme”, *Electronics & Communication Engineering Journal*, **13**, 138–144, 2001.

[65] Tu, H. and Shimamoto, S., “A Proposal of Relaying Data in Aeronautical Communication for Oceanic Flight Routes Employing Mobile Ad-Hoc Network”, Proc. of *1st Asian Conference on Intelligent Information and Database Systems*, pp. 436–441, 2009.

[66] Tunç, M. A., Perrins, E., and Sterbenz, J. P. “Performance Evaluation of a TDMA MAC Protocol in Airborne Telemetry Networks”, Proc. of *International Telemetering Conference (ITC)*, pp. 1-10, 2010.

[67] Vieira, L., Almiron, M., and Loureiro, A. A. F., “3-D MANETs: Link Probability, Node Degree, Network Coverage and Applications”, Proc. of *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 2042–2047, 2011.

[68] Wan, Y., Namuduri, K., Zhou, Y., and Fu, S., “A Smooth-Turn Mobility Model for Airborne Networks”, *IEEE Transactions on Vehicular Technology*, **62**, 3359–3370, 2013.

[69] Wang, K. and Li, B., “Group Mobility and Partition Prediction in Wireless Ad-Hoc Networks”, Proc. of *IEEE International Conference on Communications*, pp. 1017–1021, 2002.

[70] Wang, S., Fan, C., Deng, C., Gu, W., Sun, Q., and Yang, F., “A-GR: A Novel Geographical Routing Protocol for AANETs”, *Journal of Systems Architecture*, **59**, 931–937, 2013.

[71] Wargo, C. and Apaza, R., “Application Survey for the Future Aeromacs”, Proc. of *Integrated Communications, Navigation and Surveilance Conference (ICNS)*, pp. G7–1–G7–10, 2011.

[72] Xie, J., Wan, Y., Namuduri, K., Fu, S., and Kim, J. H. "A Comprehensive Modeling Framework for Airborne Networks", Proc. of *IEEE MILCOM*, pp. 458-463, 2013.

[73] Xu, K. and Gerla, M., "A Heterogeneous Routing Protocol Based on a New Stable Clustering Scheme", Proc. of *IEEE MILCOM*, pp. 838–843, 2002.

[74] Yan, J., Song, G., Li, H., Hua, C., Chen, C., and Guan, X., "Critical Transmission Range for Connectivity in Aeronautical Ad-Hoc Networks", Proc. of *10th World Congress on Intelligent Control and Automation (WCICA)*, pp. 4446–4451, 2012.

[75] Zhang, Q. and Matolak, D., "Aeronautical Relay Network Performance for Several Duplexing, Multiplexing, and Multiple Access Schemes", Proc. of *IEEE/AIAA 31st Digital Avionics Systems Conference (DASC)*, pp. 5D2–1–5D2–14, 2012.

[76] Zhou, Q., Gu, W., Li, J., Sun, Q., and Yang, F., "A Topology Aware Routing Protocol Based ADS-B System for Aeronautical Ad Hoc Networks", Proc. of *8th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM)*, pp. 1–4, 2012.