CONNECTIVITY ANALYSIS AND ITS APPLICATION TO ROUTING PROTOCOL IN AVIATION AD HOC NETWORK

Ms. Nguyen Thi Xuan My

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy Program in Electrical Engineering
Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2011

Thesis Title	CONNECTIVITY ANALYSIS AND ITS APPLICATION TO ROUTING PROTOCOL IN AVIATION AD HOC NETWORK
By	Ms. Nguyen Thi Xuan My
Field of Study	Electrical Engineering
Thesis Advisor	Assistant Professor Chaiyachet Saivichit, Ph.D.
Thesis Co-advisor	Professor Yoshikazu Miyanaga, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Doctoral Degree

. . . . Dean of the Faculty of Engineering
(Associate Professor Boonsom Lerdhirunwong, Dr.Ing.)

THESIS COMMITTEE

. . . . Chairman
(Associate Professor Watit Benjapolakul, Ph.D)

. . . . Thesis Advisor
(Assistant Professor Chaiyachet Saivichit, Ph.D)

. . . . Thesis Co-advisor
(Professor Yoshikazu Miyanaga, Ph.D.)

. . . . Examiner
(Assistant Professor Chaodit Aswakul, Ph.D.)

. . . . Examiner
(Doctor Kultida Rojviboonchai, Ph.D.)

. . . . External Examiner
(Assistant Professor Poompat Saengudomlert, Ph.D.)

##5171865721: MAJOR ELECTRICAL ENGINEERING
KEY WORDS: CONNECTIVITY / ROUTING / AVIATION AD HOC NETWORK

NGUYEN THI XUAN MY : CONNECTIVITY ANALYSIS AND ITS APPLICATION TO ROUTING PROTOCOL IN AVIATION AD HOC NETWORK, ADVISOR : ASST. PROF. CHAIYACHET SAIVICHIT, Ph.D., CO-ADVISOR : PROF. YOSHIKAZU MIYANAGA, Ph.D, 79 pp.

Traveling by air has become popular in society nowadays. The grid of flight routes covers widely all over world. Satellite communication link is the unique medium for flights when they pass over remote area outside of ground stations' coverage area. Applying ad hoc network to bypass high cost and long delay satellite links is a topic that is attracting many research. High mobility, sparse space distribution, and long communication distance are challenges in order for aviation ad hoc network (AANET) to become true. Network connectivity and communication reliability are targets of this dissertation. At first, connectivity analytical model of a general one-dimensional ad hoc network was derived. Then it was applied to present exactly the dependence of connectedness probability on system parameters of AANET on a flight path. This model can be used in network design, and to evaluate network connectivity in various conditions. The effect of connectivity on network performance was analyzed and formulated. Employing AANET characteristic that aircraft in vicinity can know position and velocity of each other, novel link longevity based routing mechanisms were proposed to improve network communication reliability. In study new routing mechanisms, we derived a new link longevity estimation model that can be applied flexibly in reality without neighbors' transmission range knowledge. Network performance can be improved by the proper value of the threshold signal to inference and noise ratio parameter of this model. We obtained the expected routing performance from the experiment of AANET within distance of $1000Nm$ between the ground station and aircraft.

Department: Electrical Engineering	Student's Signature ....
Field of Study: Electrical Engineering	Advisor's Signature ....
Academic Year: 2011	Co-advisor's Signature ....

Acknowledgements

First of all, I would like to express grateful to my advisor, Assist. Prof. Dr. Chaiyachet Saivichit. My thesis cannot be complete without him. He always gives me invaluable advices, support and facilitate me to accomplish my Ph.D study in the best condition. The second person who is not less important that I am very thankful to is my co-advisor, Prof. Yoshikazu Miyanaga. He followed my research deliberately and gave me very useful guidance, especially during my short term in Hokaido University, Japan. I would like to thank Assist. Prof. Dr. Chaodit Aswakul, who I consider as my informal co-advisor for precious advices as well as laboratory condition support. I'm really grateful Assist. Prof. Constantin Siriteanu, who enthusiastically guide me writing technique for publication. I'm also thankful to Assist. Prof. Shingo Yoshizawa for all of his help during my short term in Japan.

I sincerely thank AUN/Seed-net, Jica for finance support, making my Pd.D dream become true.

Thank all of my colleagues and good friends always beside me and willing to give me the help when I needed. Many thanks to my senior, Aj. Pek, who gave me many good comments on research and kindly supported when I encountered difficulty. When my family could not be beside me, plenty of thanks to Soe Soe, Omer, Anue, Thiri, Tri, the friends always with me as my spirit reliance.

Last, but not least, my deepest gratitude is to my mother, who sacrifices her life for my best. In spite of distance apart, but she always follows me and encourages my spirit until the end of the way. This dissertation is for her.

Contents

Chapter Page

List of Figures

List of Tables

CHAPTER I

INTRODUCTION

1.1 Motivation

Aviation is an advanced industry nowadays. In aviation, communications take an important role. Air traffic control services must rely on communication. Airline operators need communication to contact with their flight cruise. There are potential applications that aircraft need to communicate to each other. Passengers on flight also want to use communication services such as on-flight Internet.

Todays, the grid of international flight routes has covered entire global, so the widely covering global of communication infrastructure is needed. In area where ground facilities are not able or difficult to be setup such as oceans, poles and desert, satellite link is the main communication medium. Satellite communication has disadvantage of high cost and long delay. Researchers are interested in bringing mobile ad hoc network (MANET), an emerging technologies, to be applied in future aviation network as a new communication medium for aircraft in remote area.

MANET is a peer to peer communication network that is self organized by mobile nodes without relying on an available infrastructure. Network members communicate with each other based on other intermediate member nodes. A node in MANET takes two roles as user and router. It can exchange own data to others, or be a router to relay data for other nodes. Aviation ad hoc network (AANET) is a term used to indicate MANET applications in aviation. Aircraft are mobile nodes of AANET. The benefit of AANET is to expand communication scale longer than limit of a single transmission range. It can supplement additional bandwidth with lower cost and shorter delay to the limit satellite link bandwidth.

There are still challenges for AANET to be deployed in reality. Dynamic AANET topology as a result of node mobility causes links intermittent among nodes. It effects severely on network performances. Significant packet lost can happen on unstable routes, which are constructed from intermittent links. Node mobility cannot guarantee network always being connected. When network is partitioned, the communication between nodes on different parts are disable. Some work considered this network connectivity problem. [1] claimed that with long transmission range of aircraft enabled more than $600Km$ and node density of 7.6×10^{-5} as nowadays, AANET is feasible to be established. On investigation of AANET over the North Atlantic flight corridor, [2] showed that event transmission range expanding up to 300 Nm cannot guarantee every time that connections from aircraft to ground stations are established. [3] solves connectivity problem by let relaying aircraft hold transit packets when it has not yet found next node to forward packets within a certain allowing time. Many work rely on backup system as satellite links to improve connectivity for AANET. There has not been yet any research analyzing network connectivity for the relationship of network connectedness probability with various network conditions. Network connectivity is only considered as necessary condition, but the effect of connectivity condition to network performance is not carefully investigated. With the dynamic topology network as AANET, it is necessary to have a method to evaluate network connectivity in network design or determining the network applicability.

From these issues, this dissertation studied connectivity analysis modeling for AANET and the effect of connectivity conditions on network performances. Then, we studied the application of new routing mechanisms to improve communication reliability based on AANET.

1.2 Objective

The objective of this dissertation is to develop a connectivity analysis modeling of AANET which lead to being able to identify and discuss the effect of connectivity condition on network performance. From that, routing mechanisms are then proposed to improve network reliability.

1.3 Scope

The network model investigated is ad hoc based communication between aircraft and the ground station. Connectivity analysis model of AANET on a single flight path is developed. In this model, the relationship among connectedness probability and related connectivity system parameters is expressed in explicit formula. Then the impact of connectivity conditions on network performance is analyzed. From analysis results, new routing mechanism is developed for reliable communication routes between aircraft and the ground station.

Network members are civil aircraft that are stable at altitude and velocities. Distribution of aircraft on flight path as well as in area is assumed to be modeled by Poisson distribution process. All aircraft are equipped ADS-B, a kind of surveillance system in aviation based on Global positioning system (GPS) that allows aircraft in vicinity to know the presence of each other. Ad hoc networking among aircraft is established based on aircraft omnidirectional transmission range.

1.4 Literature Review

1.4.1 Aviation ad hoc networks

If AANET is implemented, it can be applied in many aviation applications, from air traffic management (ATM) to in-flight internet. A multi-hop broadcasting system has been proposed in [4] to extend aircraft surveillance area. In this system, an aircraft not only broadcasts its own state information, but also rebroadcast state information of other aircraft. This system help enhance situation awareness and safety of flights. In [3], Tu et.al. proposed a relay system that remote aircraft on oceanic routes base on intermediate aircraft to transmit data to the ground station. Another application of multi-hop ad hoc networking proposed in [1] was for aircraft to share data and internet access among each other. It helps save access internet time and decrease satellite traffic load. According to [5] and other related work about AANET, the purpose of ad hoc networking is to save high cost on satellite communication and respond to future demand of aviation communication. [5] presented a new aviation network architecture in which MANET acts as the glue between innovative data link technologies such as Outer Optical Links (OOL) and Ka-band air to air communication that can offer high rate data link for long communication range.

1.4.2 Connectivity

Network connectedness is a necessary condition for ad hoc networking to be established. In [4], the authors investigated the size of clusters that is created by connected aircraft. This work studied pure network connectivity based on node density and transmission range without considering network performance.

In a research of AANET in United States' sky in which average aircraft density of $7.6\times$

$10^{-5} aircraft/km^2$ can offer closely 100% probability of at least 2 up to a dozen aircraft within range, Sakhee et.al. in [1] claimed AANET is feasible to be established. Considering intermittent links issues between nodes, their proposed routing protocol setup and maintain routes based on stability indicators. Two kinds of indicators that they used to identify link stability is link longevity and the doppler frequency of received signal. Link longevity is computed based on the knowledge of relative positions, velocities and transmission range of neighboring aircraft. The pre-known transmission range is impractical as it is affected by many variant elements such as noise and interference. Link quality is also not considered, so the effect of network connectivity on network performances cannot be reflected precisely.

AANET connectivity in densely populated aircraft area as in Europe ([6]) and low density aircraft area as North Atlantic Corridor ([2]) were studied via simulation. Network connectivity is evaluated based on the ratio of the number of connected aircraft to the ground station to the total number of aircraft. Transmission ranges as long as 100 NM and 300 NM is assessed to be sufficient for aircraft in high and low density area, respectively, to connect with the ground station most of day time. However, network connectivity is still low at night because at that time, there are only few aircraft. From the results of research, the average link longevity between aircraft on flight can take tens of minutes long. Link between nodes is assumed ideal, so it cannot also reflect the effect of connectivity on performances of network.

The connectivity of AANET in different flight level in the same flight path is analyzed in [7]. The result showed that the isolated probability of aircraft does not depend on flight level when transmission range is long. Therefore, AANET can be considered as one dimension when it is established over aircraft along flight path, or two dimension for aircraft distributed over area.

Through literature review, there has not yet any work modeling the dependence of network connectedness probability on related connectivity parameters under explicit formula. Connectivity analysis models of general ad hoc network for one dimension and two dimension were investigated in many work. However, the connectivity analysis models for two-dimensional network until now as proposed in [8], [9], [10], [11], [12] and [13] can only present approximately the dependence of connectedness probability on system parameters of network. The work on one dimensional network such as [14], [15], [16], [17], [18], [19], [20] only model network connectivity with the constant number of nodes, so AANET with the variant number of nodes cannot be applied. [21] analyzed network connectivity based on node density, in which fixed and mobile nodes distribute along a flight path together. In this connectivity analysis model, connectedness of a mobile node with at least one of the fixed nodes is demonstrated. The model proposed in [22] can model the one dimensional network connectedness probability on node density, transmission range, and distance in closed formula. However the accuracy of method to obtain the solution need to be more considered. The result is the solution of the first order linear delay differential equation with the initial condition of distance in which connectedness probability is 1 within the interval [0,R] as the transmission range. The limit of this method is the discontinuousness of the initial condition at the transmission range border. This is the weakness that author also admitted. Considering the effect of aircraft mobility on network connectedness, [23] and [24] investigated the similar mobility model but for free flow traffic of vehicle on highways. Nevertheless, they could not produce an explicit connectedness probability expression. In this work, we studied connectivity analytical modeling of AANET along a flight path. We also analyze the effect of connectivity conditions on network performance.

1.4.3 Routing protocol

After network is connected, a routing protocol takes an important role to network performances. Most of the existing routing protocols proposed for AANET employ positions and velocities knowledge from ADS-B, which is a surveillance application in Air Traffic Management (ATM) system.

The routing protocols proposed in [25] is the integration of Greedy Perimeter Stateless Routing (GPSR) and ADS-B. GPSR is a routing protocol that the current node bases on its relative positions to neighboring nodes as well as the destination to select the next forwarding packet node.This routing protocol offers high network performance in high node density condition as probability is high to find the next node while it does not require overhead for route establishment and maintenance. However, in low node density condition, packets are easy to be forwarded to a node that cannot find the better node to continue to forward packets. This problem can cause packet lost or take long delay for route discovery. Similarly, [2] also proposed position-based greedy forwarding for packets between aircraft and ground stations. This technique is pure greedy forwarding without route recovery when packet is forwarded to the node that cannot find better forwarding node. It leads to packet drop even though there may exist connection between the source aircraft and the ground station. This method is also proposed by Ha et. al. in [3] to apply AANET in relaying system to deliver packets from aircraft to the ground station on oceanic routes. To solve the connectivity problem, this routing mechanism lets aircraft hold packet for certain time when it cannot find any next node that can forward packet to the ground station. The authors also considered link quality for packet delivery success. Threshold $SINR$ of received signal between nodes to each other is used as a criteria for link establishment. Also considering link quality, threshold $SNIR$ is used in transmission range and link longevity estimation model in our work.

Beside position-based routing, proactive and reactive are two other typical routing approaches. For the proactive routing approach, each node maintains a table containing routes to other member nodes. Conversely, routes in the reactive approach are only discovered on demand . The proactive approach requires high routing overhead for route maintenance, while the reactive approach consumes long delay for route establishment. [26] proposed Adhoc Routing Protocol for Aeronautical Mobile Ad hoc Networks (ARPAM) as the hybrid of these two approaches. ARPAM is the combination of Ad hoc On Demand Distance Vector (AODV) and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF). Routes between aircraft are reactively established by AODV ([27]). The important routes connecting aircraft and ground stations is pro-actively maintained by TBRPF ([28]).

Considering communication reliability over AANET, Ehssan Sakhaee et al. in [1] proposed a new reactive routing protocol as multi-path doppler routing (MUDOR) that can establish stable route based on doppler frequency shift of received signal. Another stability indicator that authors considered is link longevity. Link formation characteristics were thoroughly analyzed in [29]. The authors proposed Hello message broadcast scheme with adaptive broadcast interval time reduce broadcast overhead while nodes can still catch up with topology dynamic change. However, this technique requires delaying time for nodes to acquire statistical link changing rate. The weakness of the existing link-longevity based routing mechanisms is the pre-knowledge requirement of transmission range. Being impacted by multi variant factors such as noise and interference, transmission range can vary and different for different nodes.

Some protocol architectures for ANET were investigated in [30]. Two architectures recommended are that MANET routing protocol resides at the IP layer and function as an IP routing protocol, or at a separated layer between the IP layer and the data link layer. The protocol architecture proposed in [5] can support multi transmission medium. It allows backup system to operate in parallel with AANET. The Advanced Link Management Algorithm (ALMA) as proposed in [31] locate at a separated layer under IP layer and above data link layer to handle data links for data transmission. Data link issues are out of the scope of this work. We only consider data traffic handling on ad hoc networking.

For applications such as air traffic control services that the data traffic flows from aircraft in network direct to the ground stations, when traffic increases over a certain level, the ground stations or nodes in their around area quickly get congested. Network architectures with multi-ground stations placed in different locations with the assistance of backup systems are solution as proposed or investigated by many work such as [2], [5], [32] and [33] and [34]. These architectures cannot only mitigate congestion problem, but also improve connectivity of network. [2] proposed ground station selection scheme based on route hop count from aircraft to the ground station. This scheme is supplemented with packet delay criteria as proposed in [34]. In this work, we focus on scalability of network with only one ground station. It is a foundation for system design of multi-ground station network.

1.5 Background

1.5.1 AANET

AANET is a kind of MANET in which mobile nodes are aircraft. Communications between aircraft, or between aircraft and ground stations can take place over direct link or on connections constituted by links among intermediate nodes.

Although AANET is opportunistically established over high mobility aircraft, aircraft when enroute are stable at altitude and velocity. The direction of aircraft is kept unchanged along a flight path. Therefore, mobility modeling for enroute aircraft can be considered as constant velocity and constant direction.

Aircraft flying in the same flight path can be in different levels. In vertical view, flights can be overlapped regarding aviation law of minimum separation in horizon between aircraft. Aircraft position distribution in snapshots along flight path can be seen as uniform random distribution. The flight levels of enroute flights concentrate at altitude interval $[8 - 11]Km$. The interval between level is 300m or 600m, which is much smaller than the transmission range required at order of hundreds Nm for AANET to be enabled. Therefore, vertical distance between aircraft can be ignored and AANET can be simplified as one dimensional network when it is considered along flight path or two dimensional when its node members distribute randomly in area.

Transmission technology candidates for AANET as mentioned in [5] are high speed directional data links as Ka band and free space optic (OOL), and omnidirectional data link as VHF. The related issues to physical and data link layers are out of scope of this dissertation. We only apply $SINR$ metric of received signal and packet queuing time at MAC layer in our proposed routing mechanisms with the assumption of under omnidirectional data link. The signal propagation in aviation environment complies free space propagation model which is described in [35] as:

$$\frac{P_r}{P_t} = \left[\frac{\sqrt{G_l}\lambda}{4\pi d}\right]^2, \tag{1.1}$$

where P_t and P_r, respectively, are transmitting and receiving signal powers. λ is the signal wavelength. $\sqrt{G_l}$ is the product of the transmitted and received antenna gains. d is the distance between the transmitting and the receiving nodes. As being experimented and analyzed in [3], the free space model can be applied for the transmission distance up to 350 Nm. We derived our longevity estimation model by employing this model.

In civil aviation, ADS-B is a surveillance system belonging to the Communications, Navigation and Surveillance infrastructure of Air Traffic Management (CNS/ATM) system. ADS-B aircraft use GPS to locate their position, then broadcast their status as an announcement of their presence to neighboring ground stations and other aircraft. The operation frequency of ADS-B is 1090MHz. We assume all aircraft are ADS-B-enabled. Therefore, position and velocity of an aircraft are available to all ground stations and other aircraft within its coverage.

1.5.2 Network connectivity

As AANET is created on mobile nodes as aircraft, partitioning and merging in alternation is the coherent characteristic of this kind of networks. When network is partitioned, nodes in different partitions cannot communicate to each other. The capability of a connection existing between two nodes depends on their distance, node density, transmission range and is expressed as connectedness probability. A task of this work is to model precisely this relationship of AANET on a flight path in explicit formulas. The derived model can be used to evaluate network connectivity or to determine critical values of system parameters according to connectivity requirements of network.

The node concept used in this work is to indicate aircraft and ground stations. Aircraft are mobile nodes and ground stations are static nodes. Being enroute, mobile nodes in AANET have high velocities around $[200 - 250]m/s$. When two nodes are inside transmission range of each other, a direction link between them is established. Two nodes outside transmission range of each other are connected if there exist between them a connection made up from link of other intermediate nodes. As AANET is modeled as one dimensional network on a flight path, the connectedness probability between two nodes is also the connectedness probability of network among nodes between them. Therefore, this connectedness probability depends on node density, transmission range, and their distance. The connectedness distance is defined as the maximum distance between two nodes that their connectedness probability is not lower than a requirement. The benefit of ad hoc networking is expressed by the multiple of communication distance to a single transmission range. This multiple coefficient is defined as extension factor of a network. The critical values of related connectivity parameters such as node density, transmission range are the values needed to be achieved in order for connectedness probability to satisfy requirement within the given connectedness distance. High connectedness probability often requires high node density. Unfortunately, high node density raises the contention in network, which in turn degrades network performance.

In connectivity analysis, ideal transmission range is assumed to simplify the task. Ideal transmission range is a concept to indicate an area around a node inside which other nodes can received successfully packet transmitted from this node with probability equal to 1, and probability is zero if they are outside this area. However, as in [36], successful packet reception depends on multi factors such as $SINR$, packet size, transmission rate and under data link technology.

Another connectivity factor affecting network performance is the stability of the connection. Low longevity connections frequently break down, rasing the number of dropped packets.

In this work, after modeling network connectivity analysis, we present the formula expressing the effect of connectivity to network performance. The conclusion from the discussion is the foundation to develop new routing techniques.

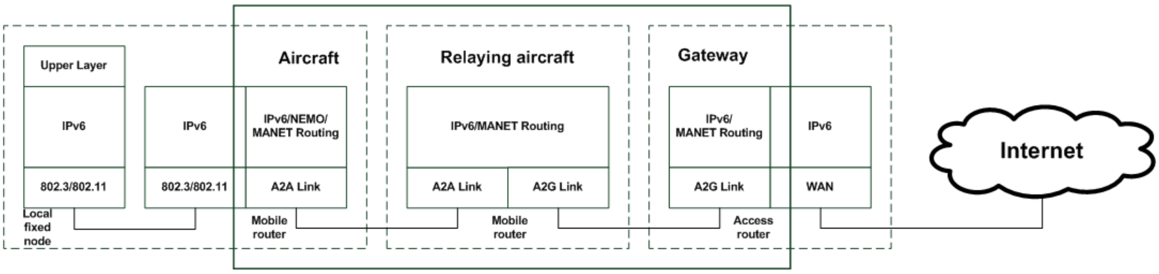


Figure 1.1: Protocol layer for IP layer MANET.

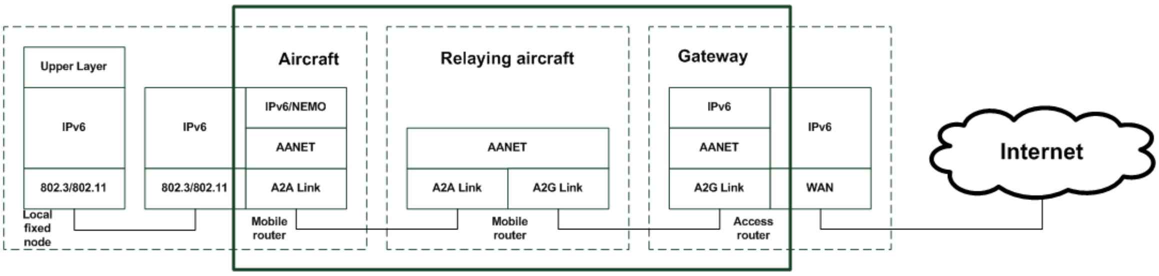


Figure 1.2: Protocol layer for Sub-IP layer MANET.

1.5.3 Routing protocol

Routing protocol is a method to find, establish, and maintain route from sources to destinations. In the protocol stack, routing protocol for AANET can locate at the IP layer as in Fig.1.1 or at a separate layer as in Fig. 1.2 specifically for AANET. When residing at the IP layer, the routing protocol only have the function to look for routes from this nodes to others. Forwarding packet from sources to destinations is handled by the IP protocol. In the second case, the routing protocol takes also responsibility of forwarding packets. Proactive, reactive, and position-based are three typical routing approaches of ad hock networking. For the proactive routing method, routes from a node to other nodes in the network is frequently updated and maintained. Contrarily, routes are only established on transmission demand in the case of the reactive routing approach. The position-based routing method heuristically forward packet by relying on neighbor at strategic positions in relation with destinations. For applications requiring persistent communications as between aircraft and the ground stations in air traffic control, the proactive routing method is better than the others as it can serve communications immediately without delay for searching routes.

Neighbor discovery, topology maintenance and route calculation are basic processes of a proactive routing protocol. In the neighbor discovery process, nodes frequently broadcast

Hello messages to enable neighbors to be aware of each other. Metrics used to evaluate link quality between neighbors can be the received rate of Hello message broadcast or characteristics of received signal such as signal strength and doppler frequency shift. For link state maintenance based on Hello message broadcast rate, high broadcast rate is required. However, broadcast overhead rate has a significant effect on network performance. It occupies data bandwidth, cause collision to data transmission, and consequently increase packet lost probability.

Link longevity between nodes can be estimated if knowledge of positions, velocities and transmission range of neighboring nodes are known by ones to others. A presentation of estimated link longevity often used by the existing work such as [1] is as following .

$$T = \frac{-(ab + cd) + \sqrt{(a^2 + c^2)r^2 - (ad - bc)^2}}{a^2 + c^2}, \tag{1.2}$$

in which,

$a = v_i \cos\theta_i - v_i \cos\theta_j$

$b = x_i - x_j$

$c = v_i \sin\theta_i - v_i \sin\theta_j$

$d = y_i - y_j$

i and j are node identifiers. $(x_{(.)}, y_{(.)})$ and $v_{(.)}$ are position and velocity of a node (.).

r is the transmission range of each node.

In this work, we study the application of link longevity in Hello message broadcast to reduce frequent broadcast rate.

Thanks to ADS-B applications, positions and velocities in AANET are available among neighbor nodes. When applying link longevity, the existing proposed routing protocols often suppose that transmission range has been known in advance. It is impractical and inflexible as transmission range is affected by multi variant elements. In this work, we proposed a dynamic technique that a node estimates transmission range based on $SINR$ of received signal from a respective neighbor. The expression (1.2) limits the link longevity estimation for only two dimension scenario. A new link longevity estimation model that we proposed in this work is more general in three dimensional space.

In order to find routes to other nodes in network, a node needs knowledge of network topology in overall. Topology maintenance is the process of topology information distribution over network. The scheme of topology information propagation depends on routing protocols. For example, with TBRPF, each node locally broadcast the tree of route from itself to other nodes in network. To reduce a great amount of broadcast information, interval time of full tree broadcast is expanded and interleaved by smaller broadcast of topology changing. For OLSR, each nodes broadcast its local links states over network. To reduce message flooding overhead, message rebroadcast is only taken by nodes in the set of Multi Point Relays (MPRs). In the investigated model that only routes between aircraft and ground stations need to be maintained, topology update overhead for all nodes in network is not essential. The proposed routing protocol in [2] for this model only diffuses ground station information over network. Aircraft unicast directly their information to their associated ground station. However, this routing protocol is position-based, so nodes maintain positions of others instead of routes.

Routes are calculated from topology knowledge. Shortest path is a traditional criterion for route selection. The shortest path can reduce collision and packet delay caused by multi-hop retransmission traffic. The route distance is measured from the route hop count. Route stability is another index that is considered in route selection. Stable route can reduce packet lost by route breaking. The route stability evaluation can be derived from the route's longevity, which is calculated as its constituted links' minimum longevity. For applications that cannot use link longevity, route stability can be indicated by the remaining time of route expired threshold. In this work, we studied to apply link longevity knowledge in routing mechanisms to improve reliability of network.

1.5.4 Simulation

The simulation is used to validate connectivity analysis model and evaluate the performance of the investigated network. To validate connectivity analysis, we use MATLAB to develop the network simulation. This simulation only consider pure network connectivity. When two nodes are in transmission range of each other, they are supposed to be connected. As network performance is affected by many other factors such as noise and interference, we develop network simulation on ns-3 foundation to evaluate performances of the network. Ns-3 is a well-known simulator for various network systems. It is developed for education and research. In ns-3, most of basic network components have been supported. They have been also verified and validated by ns-3 developers. This is an open simulator that allows researches to extend and develop new component of network.

1.6 Organization

The dissertation is structured in five chapters. In the chapter I, we introduced our overall research in this work. Our derivation of connectivity analysis model is demonstrated in the chapter II. In chapter III, we discussed the obtained network performance in different connectivity condition. Then we presented our new proposed routing mechanisms to improve the reliability of network. The experiment on implementation of the new routing mechanisms with the results are shown and evaluated in chapter IV. Finally, in chapter V, we summarized and concluded achieved results of our work.

CHAPTER II

CONNECTIVITY ANALYSIS

In this chapter, we focus on connectivity of one-dimensional ad hoc networks along a flight path. For convenience in later modeling demonstration, at first, we define some notations and concepts that will be used.

2.1 Notations

A node i in the network is denoted as n_i. A path segment j of which the length is not longer than the transmission range is denoted as s_j. When the length of s_j is equal to the transmission range, it is called *cell j* and is denoted as c_j. A network of nodes within a segment is obviously connected. A node outside the segment can be connected with that segment if it can connect to at least one node inside the segment. Two non-overlapped segments are connected when at least a node in one segment can connect with the other segment. The connectedness of two objects such as nodes, segments, or cells are denoted as $C(.,.)$. The value of $C(.,.) = 1$ if two objects are connected, and $C(.,.) = 0$ if two objects are disconnected. When the connectedness of two objects are direct, not relying on ad hoc, it is denoted as $C_d(.,.)$.

Ad hoc network applicability depends on whether network performances respond to requirements of upper applications. In this dissertation, the concepts of maximum connected distance between any pair of nodes and network coverage extension factor are introduced as evaluation metrics for aviation ad hoc network applicability. The connected distance is the longest distance that two nodes can communicate over ad hoc networking with a probability that satisfies the application requirement. Whereas, the network coverage extension factor is defined as the ratio of connected distance and transmission range.

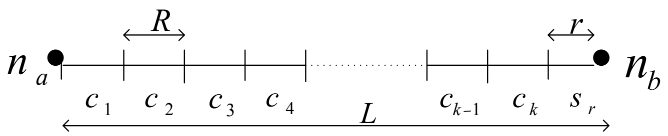


Figure 2.1: Distance between two nodes n_a and n_b is divided into cells.

2.2 General analytical connectivity model

The development of the general analytical connectivity model for one-dimensional networks is described in this section. The idea of this model development arose from a principle that two nodes can connect directly to each other when the distance between them is less than the transmission range. As being defined in section 2.1, a cell is a segment of which the length is equal to the transmission range, so that nodes locating inside the same cell can directly connect to each other. On the other hand, when two nodes are located longer than transmission range apart outside the same cell, they are considered not being directly connected. The connection can be established between these two nodes only when each node can connect to at least another intermediate node inside the cell. By dividing the distance between two nodes into cells, their connectedness can be analyzed as a series of component connectedness of a node and a cell, and pairs of adjacent cells. As a result, connectedness probability of two nodes separated by distance longer than the transmission range can be computed based on these connectedness probability components. Actually, this principle has been used by [23]. However, this work did not produce the closed form of the connectedness probability and the connectivity model can be applied when the node positions are uniformly distributed. Our computation technique relies on the probability density function of the node position in cells, therefore a general closed form of connectedness probability could be achieved. It can be applied to any one-dimensional network models as long as the probability density function of the closest node position from each side of the cells could be determined.

In Fig.2.1, two nodes n_a and n_b on a path are depicted. The transmission range of each node is R. By dividing the distance L between two nodes into cells, n_a belongs to the cell c_1, and n_b is separated from the cell c_k by a segment s_r. The length of s_r is $r = L - kR$. k is the number of cells between n_a and n_b such that $k = \lfloor \frac{L}{R} \rfloor$. n_a and n_b are connected when all pairs of adjacent cells from c_1 to c_k, as well as c_k and n_b are connected. This connectedness can be represented as follows:

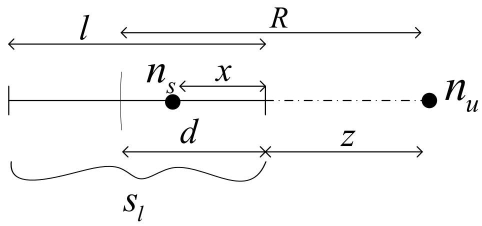


Figure 2.2: Nodes n_u is connected to segment s_l when there exists a node n_s in the interval d under n_u transmission range.

$$C(n_a, n_b) = \bigcap_{i=1}^{k-1} \big(C(c_i, c_{i+1})\big) \cap C(c_k, n_b). \tag{2.1}$$

From the basic probability theory, we have $P\{A \cap B\} = P\{A\}P\{B|A\}$, where A and B are logic events as an example. $C(c_i, c_{i+1})$ is affected only by $C(c_{i-1}, c_i)$, and $C(c_k, n_b)$ is also affected only by $C(c_{k-1}, c_k)$. Therefore, (2.1) yields the connectedness probability as:

$$\begin{aligned} P\{C(n_a, n_b)\} = P\{C(c_1, c_2)\} \prod_{i=2}^{k-2} \big(P\{C(c_i, c_{i+1}) | C(c_{i-1}, c_i)\}\big) \\ \times P\{C(c_k, n_b) | C(c_{k-1}, c_k))\}. \end{aligned} \tag{2.2}$$

2.2.1 Direct connectedness probability of a node and a segment

A node n_u and a segment s_l of length l separated by distance $z \le R$ are illustrated in Fig.2.2. The transmission range of n_u overlaps the segment s_l an interval d equal to $R - z$. Node n_u is directly connected to s_l when at least a node exists inside the interval d. In other words, the closest node inside s_l as n_s to n_u has to be within d. By taking the s_l border closer to n_u as the reference origin, the probability density function (pdf) of the closest position x that exists a node n_s to n_u is denoted as $f_{s_l}(x)$. Therefore, the direct connectedness probability of n_u and s_l is computed as follows:

$$\begin{aligned} &P\{C_d(s_l, n_u) \big| \|s_l, n_u\| = z\} \\ &= \int_0^d f_{s_l}(x)dx = \int_0^{R-z} f_{s_l}(x)dx, \end{aligned} \tag{2.3}$$

where $\|s_l, n_u\|$ is the distance between s_l and n_u.

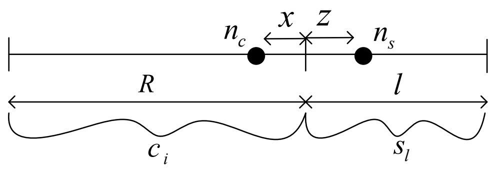


Figure 2.3: Cell c_i and segment s_l are connected when c_i can directly connect with the closest node n_s in s_l.

2.2.2 Connectedness probability of a cell and an adjacent segment

Fig.2.3 illustrates a cell c_i adjacent to a segment s_l. c_i and s_l are connected when c_i can directly connect with the closest node in s_l. Denoting the closest node as n_s, the connectedness probability of c_i and n_s can be computed by using (2.3). Let the border between c_i and s_l be the reference origin, $f_{c_i}(x)$ be the pdf of the closest node position to the origin in c_i, $f_{s_l}(z)$ be the pdf of the closest node position to the origin in s_l. The connectedness probability of c_i and s_l is computed as:

$$\begin{aligned} &P\{C(c_i, s_l)\} = P\{C_d(c_i, n_s)\} \\ &= \int_0^l P\{C_d(c_i, n_s) \big| \|c_i, n_s\| = z\} f_{s_l}(z)dz \\ &= \int_0^l \int_0^{R-z} f_{c_i}(x) f_{s_l}(z) dxdz. \end{aligned} \tag{2.4}$$

This outcome is applied to find the connectedness probability of adjacent cells in the next section.

2.2.3 Connectedness probability of adjacent cells

From (2.4), connectedness probability of two adjacent cells c_i and c_{i+1} is computed as:

$$P\{C(c_i, c_{i+1})\} = \int_0^R \int_0^{R-z} f_{c_i}(x) f_{c_{i+1}}(z) dxdz. \tag{2.5}$$

When c_i has been connected with c_{i-1}, it can be considered as there already exists at least one node in c_i. The probability of at least one node in a segment s_l of length l is:

$$P\{N_{s_l} > 0\} = \int_0^l f_{s_l}(x)dx. \tag{2.6}$$

Thus, the connectedness probability of c_i and c_{i+1} in this given condition is computed as:

$$\begin{aligned} &P\{C(c_i, c_{i+1})|C(c_{i-1}, c_i)\} = P\{C(c_i, c_{i+1})|N_{c_i} > 0\} \\ &= \frac{P\{C(c_i, c_{i+1})}{P\{N_{c_i} > 0\}} = \frac{\int_0^R \int_0^{R-z} f_{c_i}(x) f_{c_{i+1}}(z) dx dz}{\int_0^R f_{c_i}(x) dx}. \end{aligned} \tag{2.7}$$

2.2.4 Connectedness probability of a node and a cell

Referring to Fig.2.1, n_b can connect directly to or rely on an intermediate node in s_r to connect with c_k. According to that, the connectedness probability of n_b and c_k is formulated as:

$$\begin{aligned} &P\{C(c_k, n_b)|C(c_{k-1}, c_k)\} = \\ &P\{C(c_k, n_b)|N_{c_k} > 0\} = \frac{P\{C(c_k, n_b)\}}{P\{N_{c_k} > 0\}} \\ &= \frac{P\{C(c_k, s_r)\} + P\{C_d(c_k, n_b)\big|\|c_k, n_b\| = r\}P\{N_{s_r} = 0\}}{P\{N_{c_k} > 0\}}. \end{aligned} \tag{2.8}$$

Based on (2.3), (2.4) and (2.6), (2.8) is found as follows:

$$\begin{aligned} &P\{C(c_k, n_b)|C(c_{k-1}, c_k)\} = \\ &\frac{1}{\int_0^R f_{c_k}(x) dx} \Bigg(\int_0^r f_{c_k}(x) \int_0^{R-z} f_{s_r}(z) dz dx + \\ &\int_0^{R-r} f_{c_k}(x) dx \Big(1 - \int_0^r f_{s_r}(x) dx\Big)\Bigg). \end{aligned} \tag{2.9}$$

Finally, the solution of (2.2) is derived in the next section.

2.2.5 Connectedness probability of two nodes

The connectedness probability of two nodes n_a and n_b is derived by replacing (2.5), (2.7) and (2.9) into (2.2). Notice that the border of a cell is used as a reference origin to compute pdf of node distribution. Regarding the asymmetric pdf from the two sides of a cell, the solution of (2.2) is generalized to present as:

$$\begin{aligned} &P\{C(n_a, n_b)\} = \frac{\prod_{i=1}^{k-1} \int_0^R \int_0^{R-z} f_{nc_i}(x) f_{pc_{i+1}}(z) dx dz}{\prod_{i=2}^{k} \int_0^R f_{pc_i}(x) dx} \\ &\times \Bigg(\int_0^r f_{nc_k}(x) \int_0^{R-z} f_{ps_r}(z) dz dx + \\ &\int_0^{R-r} f_{nc_k}(x) dx \Big(1 - \int_0^r f_{ps_r}(x) dx\Big)\Bigg), \end{aligned} \tag{2.10}$$

where $f_{pc_i}(x)$ denotes $f_{c_i}(x)$ when the border of c_i with the previous cell c_{i-1} is the reference origin, and $f_{nc_i}(x)$ denotes $f_{c_i}(x)$ when the border with the next cell c_{i+1} is the reference origin. Recall that $k = \lfloor \frac{L}{R} \rfloor$ and $r = L - \lfloor \frac{L}{R} \rfloor R$.

2.3 Connectivity analysis for aviation ad hoc network

As shown in the general connectivity model in the previous section, the connectedness probability depends on the node distribution. Connectivity analysis here is for aviation ad hoc networks of enroute aircraft. Aircraft movement state can be considered stable at a certain altitude and velocity. Aircraft flights on a path are in continuous flows, so we can assume the flight path length is sufficiently long and aircraft positions are uniformly distributed in snapshots along the flight path. This assumption also corresponds to the homogenous Poisson distribution of the number of aircrafts on the flight path. As the node distribution is affected by aircraft arrival rate and velocity, it is analyzed in detail in the section 2.4.3.1 to validate for this assumption.

2.3.1 Connectedness probability

Probability that there are n nodes in an l-length segment of the ρ-density flight path according to Poisson distribution is computed as:

$$P\{N_l = n\} = \frac{(\rho l)^n}{n!} e^{-\rho l}, \tag{2.11}$$

where N_l denotes the random variable of the number of nodes in the l-length segment.

The cumulative distribution function (cdf) $F_S(l)$ for the closest node within the distance l from the reference point is also the probability that there is at least one node in a l-length segment:

$$F_S(l) = P\{S \leq l\} = P\{N_l > 0\} = 1 - e^{-\rho l}, \tag{2.12}$$

where S is the random variable of the considered distance. It results in the pdf $f_S(l)$ of the closest node at distance l:

$$f_S(l) = \frac{dF_S(l)}{dl} = \rho e^{-\rho l}. \tag{2.13}$$

Applying (2.13) to the general connectivity model in (2.10), the connectedness probability of two aircraft with transmission range R, separated by distance L on a path with density ρ is computed as:

$$P_c(L,R,\rho) = \left(\frac{1 - e^{-\rho R} - \rho R e^{-\rho R}}{(1 - e^{-\rho R})}\right)^{\lfloor \frac{L}{R} \rfloor - 1} \times \left(1 - e^{-\rho R} - \rho(L - \lfloor \frac{L}{R} \rfloor) e^{-\rho R}\right), \tag{2.14}$$

where $P_c(...)$ denotes the connectedness probability of two aircraft. Parameters inside the parentheses are those main parameters used to determine the value of connectedness probability . We also use these notations for later representations of connectedness probability in this dissertation.

2.3.2 Coverage extension

We have found above the probability of two aircraft being connected in ad hoc networking environment. Now, we evaluate the ad hoc networking application efficiency based on coverage extension factor and connected distance metrics. As defined above, connected distance is the longest distance between two nodes that the connectedness probability satisfying connectivity requirement. Network coverage extension factor is used to denote the ratio between the connected distance and the transmission range.

By substituting the average number of nodes in the transmission range $\alpha = \rho R$ and ratio $\beta = \frac{L}{R}$ into (2.14), we obtain the connectedness probability of two nodes as a function of α and β:

$$P_c(\alpha,\beta) = \left(\frac{1 - (1+\alpha)e^{-\alpha}}{(1 - e^{-\alpha})}\right)^{\lfloor \beta \rfloor - 1} \times \left(1 - (1 + \alpha(\beta - \lfloor \beta \rfloor))e^{-\alpha}\right). \tag{2.15}$$

If the connectivity requirement is p_0, aircraft can only communicate with others within the range $\beta \leq \beta_0$ to guarantee the connectivity requirement:

$$P_c(\alpha,\beta) \geq p_0, \tag{2.16}$$

where β_0 is the network coverage extension factor, i.e. the root of (2.16) in case of equality. It is found as:

$$\beta_0 = \lfloor \beta_t \rfloor + \frac{1}{\alpha}\left(\left(1 - p_0\left(\frac{1 - e^{-\alpha}}{1 - (1+\alpha)e^{-\alpha}}\right)^{\lfloor \beta_t \rfloor - 1}\right)e^{\alpha} - 1\right), \tag{2.17}$$

with

$$\beta_t = \frac{\ln \frac{p_0}{1-e^{-\alpha}}}{\ln \frac{1-(1+\alpha)e^{-\alpha}}{1-e^{-\alpha}}} + 1 = \frac{\ln \frac{p_0}{1-e^{-\rho R}}}{\ln \frac{1-(1+\rho R)e^{-\rho R}}{1-e^{-\rho R}}} + 1. \tag{2.18}$$

(Derivation detail is shown in the appendix.)

As a result, the corresponding connected distance is:

$$\begin{aligned} L_0 &= R\beta_0 \\ &= R\lfloor\beta_t\rfloor + \frac{1}{\rho}\Bigg(\bigg(1 - p_0\Big(\frac{1-e^{-\rho R}}{1-(1+\rho R)e^{-\rho R}}\Big)^{\lfloor\beta_t\rfloor-1}\bigg)e^{\rho R} - 1\Bigg). \end{aligned} \tag{2.19}$$

2.4 Impact of mobility on network connectedness

2.4.1 Impact of arrival rate and velocity on network connectedness

The above derivations indicate that network connectedness depends on node distribution, node density, and transmission range. Radically, node density depends on node arrival rate and average velocity in the considered flight path. The relationship among arrival rate, velocity, and density can be observed by a simple example. A node n_a is moving along a path of length l with average velocity v in time $t = \frac{l}{v}$. During this time, other nodes also enter the path with arrival rate λ. Therefore, when node n_a reaches the other end of the path, there are $N = \lambda t$ nodes in the path. The density of nodes on the path as a result is:

$$\rho = \frac{N}{l} = \frac{\lambda}{v}. \tag{2.20}$$

With constant arrival rate and average velocity, this density ρ is constant. Replacing (2.20) into (2.14), the connectedness probability of two nodes on the node arrival rate and velocity is represented as:

$$\begin{aligned} P_c(L, R, \lambda, v) = &\left(\frac{1 - e^{-\frac{\lambda R}{v}} - \frac{\lambda R}{v}e^{-\frac{\lambda R}{v}}}{(1-e^{-\frac{\lambda R}{v}})}\right)^{\lfloor\frac{L}{R}\rfloor-1} \\ &\times \left(1 - e^{-R(\sum_{j=1}^{m}\frac{\lambda_j}{v_j})} - \frac{\lambda}{v}(L - \lfloor\frac{L}{R}\rfloor)e^{-R(\sum_{j=1}^{m}\frac{\lambda_j}{v_j})}\right). \end{aligned} \tag{2.21}$$

2.4.2 Multi-velocity class traffic

Aircraft velocity on the path depends on aircraft type or specific conditions. We divide air traffic on the path into m classes. Aircraft in each class have the same average velocity. Class j has arrival rate λ_j and velocity v_j. Aircraft density will be the sum of densities from different classes:

$$\rho = \sum_{j=1}^{m}\frac{\lambda_j}{v_j}. \tag{2.22}$$

This leads to the connectedness probability of two nodes as in (2.14):

$$
\begin{aligned}
&P_c(L,R,\lambda,v) = \\
&\left(\frac{1-e^{-R\left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}} - R\left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}e^{-R\left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}}}{(1-e^{-R\left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}})}\right)^{\lfloor\frac{L}{R}\rfloor-1} \\
&\times\left[1-e^{-R\left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}} - \left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}\left(L-\lfloor\frac{L}{R}\rfloor\right)e^{-R\left\{\sum_{j=1}^{m}\frac{\lambda_j}{v_j}\right\}}\right].
\end{aligned}
\tag{2.23}
$$

2.4.3 Impact of arrival rate and velocity on node distribution

As shown in the proposed general connectivity model in section 2.2, network connectedness depends on the node distribution along the path. In order to understand the effect of mobility on network connectedness, we analyze the effect of mobility on node distribution along the path.

Considering a path segment, an inbound traffic flow of nodes entering this segment yields a Poisson process with an arrival rate λ and an average velocity v. The probability that there is at least one node within distance x from the entry point represents the cdf $F_X(x) = P\{X < x\}$. This is also the probability of finding the closest node to the entry point within distance x from the entry point at an arbitrary time. If the relationship of node position and time can be represented by a function $X = g(T)$, position distribution $F_X(x)$ can be computed based on time distribution as:

$$
\begin{aligned}
F_X(x) &= P\{X \le x\} = P\{g(T) \le x\} \\
&= P\{T \le g^{-1}(x)\} = 1 - e^{-\lambda g^{-1}(x)}.
\end{aligned}
\tag{2.24}
$$

As a result, pdf $f_X(x)$ to find the closest node at distance x will be:

$$
f_X(x) = \frac{dF_X(x)}{dx} = \lambda e^{-\lambda g^{-1}(x)}\frac{dg^{-1}(x)}{dx}. \tag{2.25}
$$

At an entry point of a segment, node position distribution of an outbound traffic flow at each point along the segment can be considered as the same of the inbound flow which has the same arrival rate and inverse velocity changing behavior, such that the average velocity are the same for two opposite flows at each point along the flight path. Therefore, when considering an outbound flow, we can apply (2.24) and (2.25) for its corresponding inbound flow.

With this distribution modeling, we now present some traffic scenarios as follows.

2.4.3.1 Aircraft travel with constant velocity:

Most enroute aircraft travel at a constant velocity at a certain flight level along a flight path for a significant period of time. The aircraft velocity v is constant along the path. Therefore, $X = vT$. (2.24) and (2.25) become as a consequence:

$$\begin{aligned} F_X(x) &= P\{X \leq x\} = P\{vT \leq x\} = P\{T \leq \frac{x}{v}\} \\ &= 1 - e^{-\frac{\lambda x}{v}} = 1 - e^{-\rho x}, \end{aligned} \tag{2.26}$$

and

$$f_X(x) = \frac{\lambda}{v} e^{-\frac{\lambda x}{v}} = \rho e^{-\rho x}. \tag{2.27}$$

This is the case considered in section 2.3 (see (2.12) and (2.13).)

2.4.3.2 Aircraft travel with acceleration:

An aircraft enters a segment with velocity v and this changes with constant acceleration a when moving along the segment.

The relationship between position and time for this scenario is $X = \frac{a}{2}T^2 + vT$. Therefore, aircraft position distribution from segment entry is $F_X(x)$:

$$\begin{aligned} F_X(x) &= P\{X \leq x\} = P\left\{\frac{a}{2}T^2 + vT \leq x\right\} \\ &= P\left\{T \leq \frac{-v + \sqrt{v^2 + 2ax}}{a}\right\} \\ &= 1 - e^{-\frac{\lambda}{a}(-v+\sqrt{v^2+2ax})}. \end{aligned} \tag{2.28}$$

$$f_X(x) = \frac{\lambda}{\sqrt{v^2 + 2a}} e^{-\frac{\lambda}{a}(-v+\sqrt{v^2+2ax})}. \tag{2.29}$$

2.4.3.3 Various velocity aircraft on a flight path:

Air traffic on a flight path can be classified into some classes. Aircraft in the same class have similar movement behavior and similar velocity. On a certain flight path stage, there can be classes with constant velocity, or classes of which aircraft travel with acceleration. The cdf of aircraft position of a class j is $F_{Xj}(x)$. As aircraft can fly in different flight level, their mobility can be considered as independent. Therefore, the distribution of aircraft position

$F_X(x)$ of having at least one aircraft in distance x from a segment entry can be computed based on aircraft position distribution from each corresponding class:

$$F_X(x) = 1 - \prod_{j=1}^{m}(1 - F_{Xj}(x)). \tag{2.30}$$

We assume there are m classes on a considered flight path. In a segment of flight path, aircraft in k classes move with constant speed and in h classes with acceleration. Applying (2.26) for class with constant velocity and (2.28) for class with accelerating aircraft into (2.30), (2.24) becomes:

$$\begin{aligned} F_X(x) &= 1 - \prod_{i=1}^{k}(e^{-\frac{\lambda_i x}{v_i}})\prod_{j=1}^{h}(e^{-\frac{\lambda_j}{a_j}(-v_j+\sqrt{v_j^2+2a_j x})}) \\ &= 1 - e^{-x\sum_{i=1}^{k}\frac{\lambda_i}{v_i}-\sum_{j=1}^{h}\frac{\lambda_j}{a_j}(-v_j+\sqrt{v_j^2+2a_j x})}, \end{aligned} \tag{2.31}$$

so:

$$\begin{aligned} f_X(x) = &\left(\sum_{i=1}^{k}\frac{\lambda_i}{v_i} + \sum_{j=1}^{h}\frac{\lambda_j}{\sqrt{v_j^2+2a_j x}}\right) \\ &\times e^{-x\sum_{i=1}^{k}\frac{\lambda_i}{v_i}-\sum_{j=1}^{h}\frac{\lambda_j}{a_j}(-v_j+\sqrt{v_j^2+2a_j x})}. \end{aligned} \tag{2.32}$$

where λ_i is the arrival rate of the class i, v_i is the velocity of nodes in the class i if the average velocity of this class is constant. If the average velocity of the class i is changed with the acceleration a_i, v_i denotes the node velocity at the entry point.

When aircraft velocity behavior is different in each stage of a flight path, (2.24) and (2.25) can be applied to compute aircraft position distribution in the connectivity model presented by (2.10). So far, we have presented a comprehensive modelling of aircraft travelling at each stage along a flight path. This modelling is considered to be an effective modelling of aircraft connectedness on any flight path.

2.5 Numerical result and validation

In this section, simulation based on MATLAB system was conducted to validate the proposed connectivity model. Then, the feasibility and applicability of aviation ad hoc networks were discussed on the result of the model.

Aircraft flying on a flight path of 6000 NM length was simulated. At first, the simulation was set up only for the case of single air traffic class on the flight path. Aircraft in flight

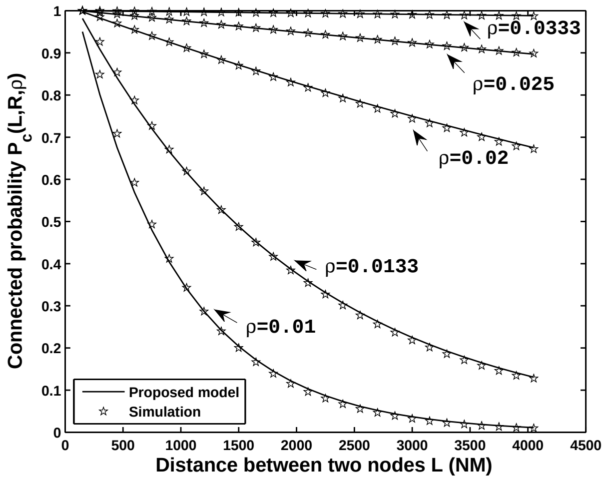


Figure 2.4: Connectedness probability between two aircraft having transmission range R=150 NM on the path with density ρ (aircraft/NM).

are in either direction of continuous flows from two ends of the path. At the initial setup stage, an exponential random generator of aircraft position was used to generate the distance between aircraft on each flow. This assignment determines the locations of aircraft along the flight path. The mean value fed to the generator is computed from a given aircraft density. We implemented simulation with some values of aircraft density as depicted in Fig.2.4. Because the number of aircraft is contributed from flows in two opposite directions on a flight path, the density of aircraft on each direction is one half of the total density. Aircraft shall travel on the flight path with a mobility model that their velocities were kept unchanged from one end to the other end of that flight path. By assuming that aircraft velocity in the same class is normally distributed, a normal random generator was used to generate velocity of aircraft of which recently were generated by position generator. The velocity generator is set with the mean value of velocity at 450 NM/hour and variance of 5 NM/hour. The values of these parameters were selected randomly from the actual range of aircraft velocity. We also implemented the simulation with some other values of these parameters and found out that the mean velocity does not have significant effect on the result. It is a consequence from the fact that the aircraft density remains the same when the arrival rate changes with velocity as shown in (2.20).} The mean inter-arrival time is computed from aircraft arrival rate and fed to the exponential random number generator of the inter-arrival time value. This generator was used to generate the aircraft arrival time at each end of the flight path during simulation. The velocity generator was also used in the simulation for new aircraft velocity assignment.

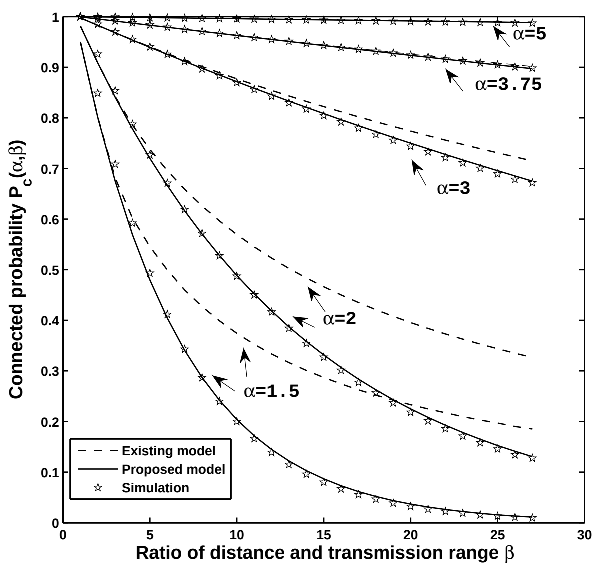


Figure 2.5: Connectedness probability between two nodes on the path depending on β (distance between aircraft/transmission range) and α (the number of aircraft/transmission range).

The transmission range assigned for each aircraft in this simulation case was 150NM.

The simulation running time corresponded to 10000 observing hours. The connectedness probability was measured by connectedness measurement of points along the flight path to the point in the middle of the flight path that is taken as the reference point. A point is said to be connected with the reference point if a series of "connectedness" over intermediate aircraft can be established between that point and the reference point. The connectedness value was measured every 5 minutes of update interval. Each point along the flight path was accompanied with a connectedness counter. For each update, if a point was connected with the reference point, its counter increased by 1. The counter value to the total update times ratio acquired from simulation represented the connectedness probability of the corresponding point to the reference point. The points selected for connectedness measurement were at distance of multiple β of transmission range to the reference point. The simulation results and theoretic numerical results regarding connected distance upon density were presented in Fig.2.4. The results from our proposed model matched well with the simulation results and also compared with the results from the model presented by Eq.(1) in [22].

The corresponding graph regarding parameters β on the average number of aircraft α in transmission range is shown in Fig.2.5. In this graph for each α, network coverage extension factor β_0 representing the minimum value of β for connectedness probability to be higher

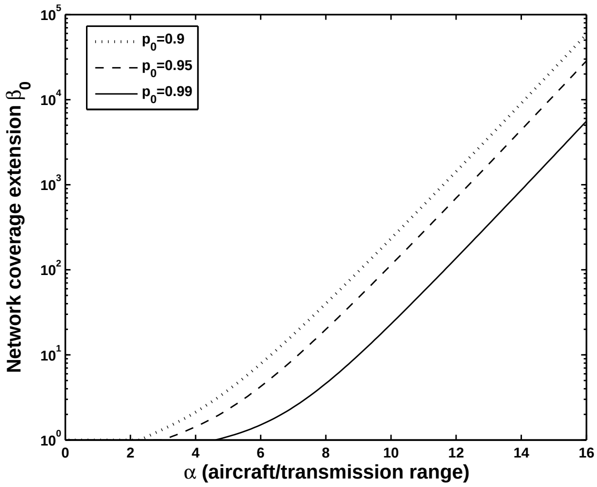


Figure 2.6: Coverage extension capability of network in different condition of the average number of aircraft in transmission range within which connectivity requirement is still satisfied.

than probability requirement was determined. Through proper validation of our proposed model, β_0 could be computed from (2.17) as shown in Fig.2.6. It can be used to evaluate the ad hoc applicability for each connectivity requirement. Following is some discussions based on the proposed model result.

As shown in Fig.2.6, larger network coverage extension is at lower connectivity requirement. That means ad hoc networking is more applicable for applications requiring lower availability. For applications requiring high availability such as air traffic control, a significant number of aircraft with the same transmission range are needed. As an example, connectivity requirement of 0.99 needs at least 9 neighboring aircraft while connectivity requirement of 0.9 needs only 6 neighboring aircraft in order to extend the connected distance 10 times the transmission range. Therefore, in each certain condition of aircraft density, transmission range should be adjusted to achieve the required value of the parameter α. Low density requires long transmission range. However, the technology limitation for long transmission range makes it impossible for the requirement to be met. Fig.2.7 shows the connected distance that can be achieved depending on critical values of aircraft transmission range as computed in (2.19). If the transmission range is limited by technology for 400 NM, the expected connected distance of 10000 NM, as an example, under density condition of $\rho = 0.02$ aircraft/NM as being shown in Fig.2.7 is infeasible. Meanwhile, $\rho = 0.05$ aircraft/NM of density condition requires only 200 NM of critical transmission range, so 10000

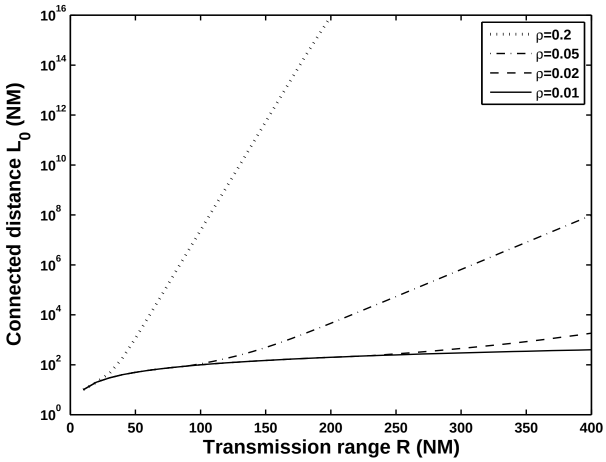


Figure 2.7: Maximum distance aircraft can communicate with probability satisfying connectivity requirement of 0.99 in different aircraft density condition.

Table 2.1: Ratio of traffic flows with different velocity

Velocity (NM/hr)	400	500	550
Set 1	0.5	0.3	0.2
Set 2	0.2	0.3	0.5
Set 3	0.2	0.5	0.3
Set 4	0.4	0.3	0.3

NM of connected distance could be achievable.

Combining (2.19) with (2.20), the dependency between connected distance and arrival rate can be presented as in Fig.2.8. Because the safety gap time of 3 minutes between aircraft taking off is required, arrival rate can be considered as lower than 20 aircraft/hour. As an example being shown in Fig.2.8, in high mobility area where average velocity of aircraft is 500 NM/hour and aircraft transmission range 100 NM, it is infeasible for 10000 NM of connected distance under condition of 0.99 network connectivity requirement because it needs higher than 20 aircraft/hour as critical value of arrival rate. When increasing the transmission range to 150NM, the critical value of arrival rate is less than 20 aircraft/hour. Therefore, this connected distance of 10000 NM can be achieved.

In order to validate the effect of velocity on the connectedness probability , we implement the simulation of a path with multi-velocity air traffic classes (i.e. three classes with average velocity of 400, 500 and 550 NM/hour.) Besides the simulation setup similar to the

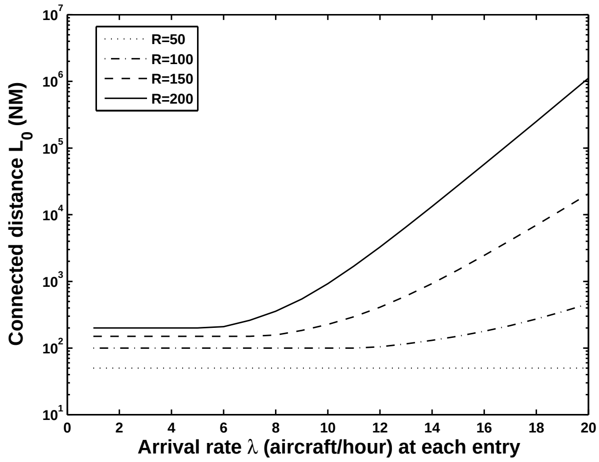


Figure 2.8: Maximum distance aircraft can communicate with probability satisfy connectivity requirement 0.99 in different aircraft arrival rate and transmission range condition. Average velocity on the path is 500 NM/hour.

single-velocity traffic class flight path, a random number generator was used for classifying the aircraft from various velocity classes into flows arriving at each end of the flight path. Other three random number generators are needed to assign velocity to aircraft based on which class that aircraft belongs to. The classifying aircraft based on a given set of ratios of flow arrival rate for each velocity class to total arrival rate at each end of a flight path. The simulation was conducted with some sets of flow arrival rate distribution as given in Table.2.1. Each row in the table represents a different set of ratio flow arrival rate distribution. The distribution of velocity-class flows determine the average velocity of aircraft on the flight path. We will see the effect of velocity to connectedness probability through simulation results of these different distribution sets. This simulation setup is similar to that of [24], but more practical when we randomly assign velocity to each aircraft based on normal distribution instead of only mean velocity. The simulation was implemented for two cases of total arrival rate at each end of the flight path $\lambda = 10$ aircraft/hour and $\lambda = 15$ aircraft/hour.

The results are shown in Fig.2.9 and Fig.2.10. They are very close to the theoretical results from (2.23). Thus, we can, with support from the comparison between simulation and analytical results, conclude that our proposed model is effective tool for the analysis. In principle, the distribution sets with high proportion of the slow velocity flow arrival rate and low proportion of the high velocity flow arrival rate contribute to slow average velocity. These sets always gives a high connectedness probability as presented in Fig.2.9 and Fig.2.10. In

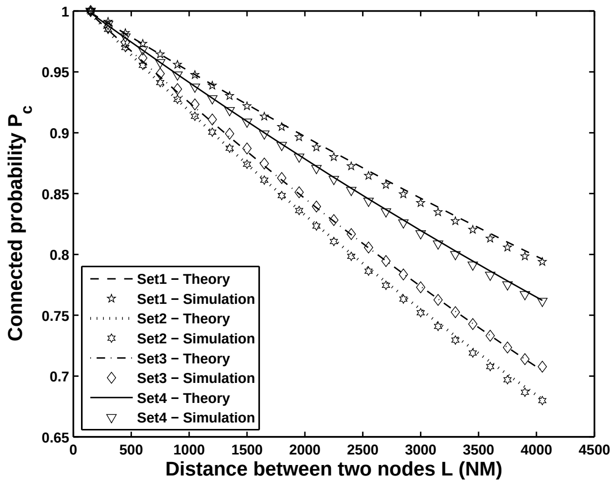


Figure 2.9: Connectedness probability between two aircraft with transmission range R=150NM on the path having multi-velocity class traffic, arrival rate in each direction is $\lambda = 10$ aircraft/hour.

this simulation, 400 NM/hour is the velocity of the slowest flow and 550 NM/h is the velocity of the fastest flow. Set 1 with the highest ratio of the slowest flow and the lowest ratio of the fastest flow produces the highest connectedness probability. Set 2 with the lowest ratio of the slowest flow and the highest ratio of the fastest flow produces the lowest connectedness probability. Another conclusion is drawn here that, the connectedness probability is low in high mobility environment.

The applicability of ad hoc aviation network upon velocity and arrival rate can also be presented as in Fig.2.11 when combining (2.19) and (2.22). Network connected distance can be extended further when aircraft move in slower velocity. As information of aircraft velocity and flight time is available in flight plan of air traffic management, the representation of the dependence of connected distance on the arrival rate and velocity as in Fig.2.11 facilitates aviation ad hoc network feasibility evaluation.

2.6 Conclusion

In this dissertation, we have proposed a general analytical connectivity model that can be applied to any one-dimensional networks. This model shows the dependence of connectedness probability of two nodes in a network on the node distribution characteristics. Then, we applied the general model for connectivity of aviation ad hoc networking along

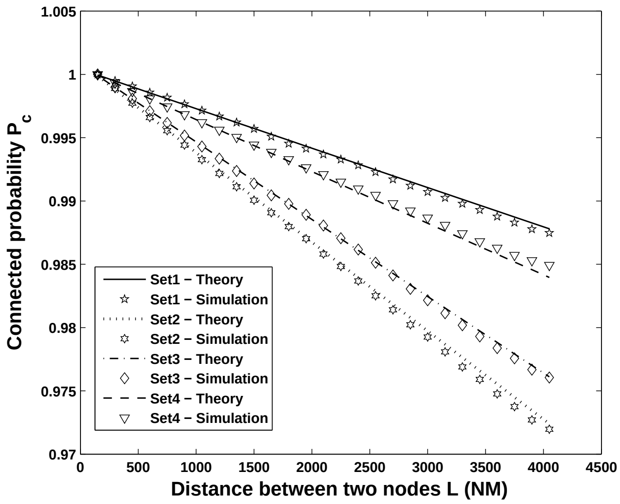


Figure 2.10: Connectedness probability between two aircraft with transmission range R=150NM on the path having multi-velocity class traffic, arrival rate in each direction is $\lambda = 15$ aircraft/hour.

a flight path that could, for example, be applied in commercial airline industry. This analytical connectivity model represents the dependence of connectedness probability, network coverage extension, and connected distance based on system parameters such as aircraft density, transmission range, velocity, and arrival rate. The impact of node mobility on network connectedness has also been analyzed. With an ability to derive the dependence of ad hoc network applicability on system parameters, our model could facilitate the ad hoc network applicability and feasibility evaluation procedure. Furthermore, an insight of this dependence is helpful in network management, network algorithms development, and network design.

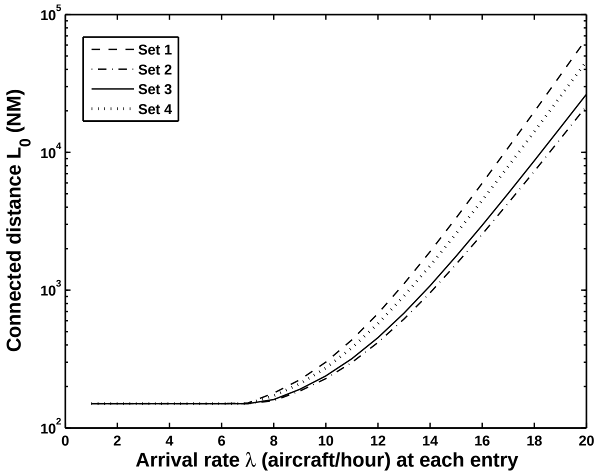


Figure 2.11: Maximum distance aircraft with transmission range R=150NM can communicate with probability satisfy connectivity requirement 0.99 in multi-velocity traffic class path.

CHAPTER III

EFFECT OF CONNECTIVITY ON NETWORK PERFORMANCE ANALYSIS AND RELIABILITY SOLUTION OF ROUTING MECHANISMS

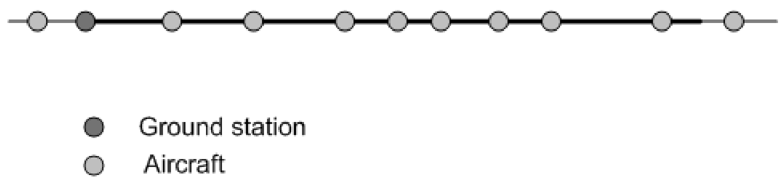
Network connectivity is a necessary condition for the feasibility of AANET. In this chapter, we present the formulation of the effect of connectivity on network performance. From the network performance analyzed issues, we proposed novel routing mechanisms to improve the communication reliability over AANET.

3.1 Network model and simulation setup

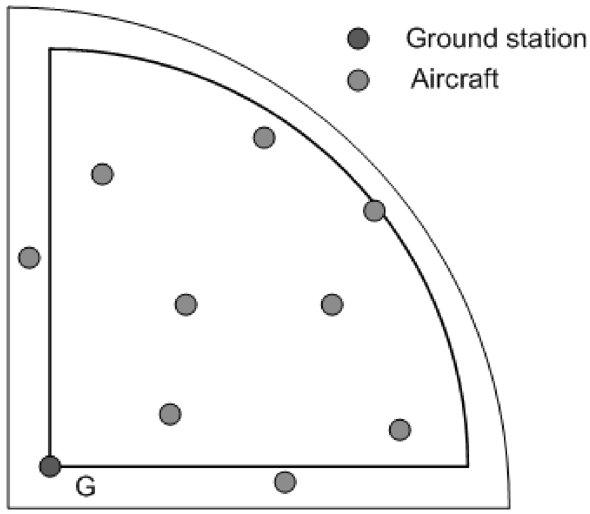
The network model addressed in this dissertation is communications between aircraft and the ground station over AANET. As vertical separation between flight levels is negligible, AANET is investigated in two scenarios as flight path-based AANET and AANET over aircraft distributed in an area. In the first scenario, aircraft move with constant velocity along two opposite directions of a line that represents for the flight path. In the case of AANET over aircraft in an area, aircraft velocity is also constant, but their direction are random. In snapshot, aircraft position distribution in the simulated area is random uniformly. Fig. 3.1 illustrates simulated space of AANET.

In order to avoid the border effect that flow of aircraft mobility is interrupted at the simulated area border, the observed area is limited inside and smaller than the simulated area. The width of the edge bounding the observed area is sufficiently large to guarantee that during the simulation time, the mobility flow at the observed area border is not interrupted .

At present, there has not been any standard of data link for AANET. As we are interested in the routing performance at the network layer, it is not a problem for which standards at the under layers to be used. We selected 802.11b for MAC and physical layers in our simulated network because 802.11 is the unique standard supporting ad hoc links today. However,



(a) AANET on a flight path



(b) AANET cover a defined area

Figure 3.1: AANET simulation

the maximum distance supported by 802.11 is constrained. We have modified this standard to increase the supported maximum distance. Due to the bandwidth for long distance is limited for data link with omnidirectional antenna, the selected bandwidth is $1Mbps$ as it is the minimum rate that 802.11b supports.

We used UDP as the transportation protocol in this simulation as the traditional TCP is not suitable for ad hoc networks. Because this investigated network does not require any new feature of IPv6, in the internet layer stack, we use the familiar IPv4. OLSR, which is a classical proactive routing protocol that has been standardized and uniquely supported by ns-3, is selected to operate as the routing protocol of the trial network. OLSR can be seen as a representative of the routing protocols that rely on the received Hello message broadcast rate to realize link states, so we used it as the benchmark for our new routing mechanisms that manage link state based on link longevity.

In network operation, every node regularly sent packets at a rate to the ground station. Various parameter values for experiment were set. Each simulation round took $1000s$. The number of iterated rounds for each simulation depends on node density condition of network. The minimum number of iterations for high node density condition is 10 times and that for low node density is 100 times. The analysis and discussion on obtained simulation results is presented in the next sections.

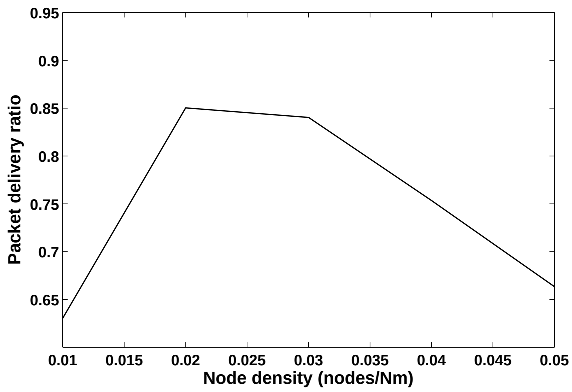
3.2 Network performance analysis

Firstly, AANET on a flight path was simulated. The simulation parameter setting is presented in table 3.1. Transmission range is distance from the transmitter position to the position that the transmit power is degraded to the reception sense threshold. Because transmission range can vary under effect of various factors such as noise and interference, the expected transmission range refers to the condition without that effect. The experimented node density interval is suitable with practical air traffic conditions that can enable AANET, where transmission range can be set within its technology achievable threshold.

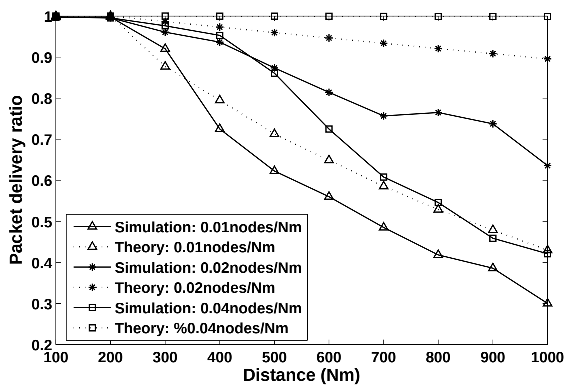
Table 3.1: Parameter setting for single flight path AANET simulation

Parameter	**Value**
Observed network length	$1000Nm$
Expected transmission range	$250Nm$
Packet sending rate of each aircraft	$2packets/s$
Packet size	$200bytes$
Node density	$0.01 - 0.05nodes/Nm$

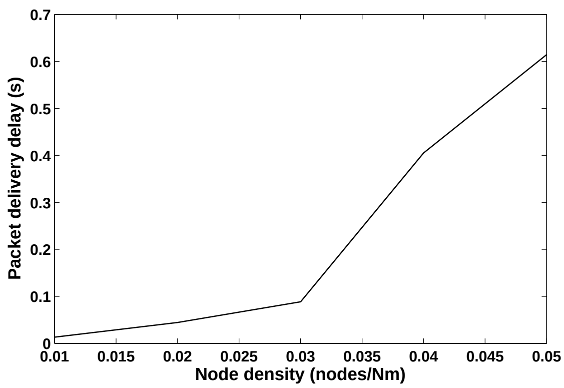
Packet delivery ratio, which is the ratio of packets successfully received by the ground station to the total packets sent by aircraft, is presented in Fig. 3.2.(a). The simulation results showed that packet delivery ratio increases with the increase of node density only in lower node density condition as $[0.01 - 0.02]nodes/Nm$. In higher node density beyond 0.03 nodes/Nm, packet delivery ratio decreases when node density increases. In statistic, packet delivery ratio can be considered as the probability of packet delivery success. Referred to network connectedness probability obtained from connectivity analysis modeling as shown in Fig. 3.2.(b), packet delivery ratio is lower. Thus, connectedness is only necessary condition for ad hoc network to be enabled. From research results of related work, network performance is also dependent on routing mechanisms. According to the routing effect on network performance, we formulated the dependence of probability of packet delivery success on routing elements as follows:



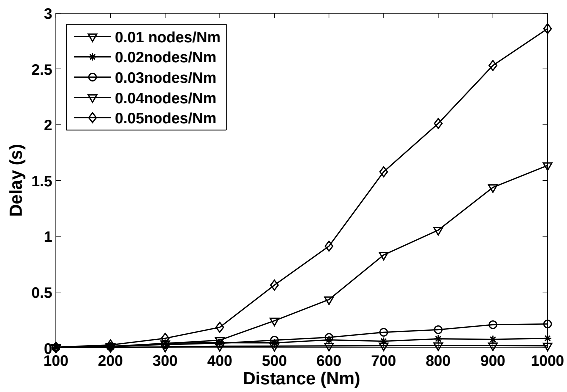
(a) The effect of node density on packet delivery ratio



(b) Comparison of packet delivery ratio with connectedness probability



(c) The effect of node density on packet delivery delay



(d) The effect of communication distance on packet delivery delay

Figure 3.2: Flight path-based AANET.

$$P_d(L, \rho, \gamma) = P_c(L, \rho) P_r(L, \rho, \gamma) P_f(L, \rho, \gamma), \tag{3.1}$$

in which:

L is communication distance.

ρ is node density.

γ is packet sending rate of each node.

$P_c(L, \rho)$ is connectedness probability

$P_r(L, \rho, \gamma)$ is the probability of at least one route to be established between the source and the destination in condition that they are connected.

$P_f((L, \rho, \gamma)$ is the probability of packet delivery success from the source to the destination in condition of route existence.

By denoting $p_i(\rho, \gamma)$ as the successful probability of packet delivery per hop i^{th}, $P_f(L, \rho, \gamma)$ can be analyzed furthered as:

$$P_f(L, \rho, \gamma) = \prod_{i=1}^{h(L)} p_i(\rho, \gamma), \tag{3.2}$$

in which $h(L)$ is the average hop count of all possible routes that can be established over communication distance L. According to (3.2), (3.1) can be rewritten as following:

$$P_d(L, \rho, \gamma) = P_c(L, \rho) P_r(L, \rho, \gamma) \prod_{i=1}^{h(L)} p_i(\rho, \gamma). \tag{3.3}$$

$p_i(\rho, \gamma)$ depends on route stability and link reliability. Such dependence can be expressed as follows:

$$p_i(\rho, \gamma) = A_i(\rho, \gamma) B_i(\rho, \gamma), \tag{3.4}$$

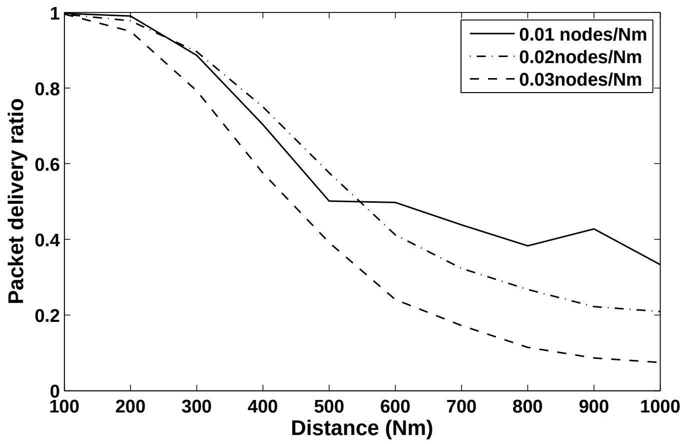
in which, $A_i(\rho, \gamma)$ and $B_i(\rho, \gamma)$ denote the availability and reliability of link at hop i^{th}, respectively. Link availability $A_i(\rho, \gamma)$ is the probability of link existence at the time the packet is delivered over it. In order to improve this performance, there are routing mechanisms that select route based on stability criteria. The proposed routing protocol in [1], which selects the most stable route for packet delivery, is an example. Link reliability $B_i(\rho, \gamma)$ is the probability of packet delivery success in condition of link availability. It depends on $SINR$ of received signal. High traffic density causes high interference and collision, making signal $SINR$ decrease and the number of dropped packets increase. The retransmission caused by the packet collision also make increase long packet delay. For the network being ”bottle neck” as the investigated model, in which traffic flows from all aircraft in network is directed to the ground station, this problem is more severe when node density increases. It is a reason that packet delivery delay is drastically increased when node density increases higher than a certain level as shown in Fig. 3.2.(c), (d). Therefore, the objective of many routing research is to find better solutions to mitigate traffic overhead in network. The shortest path is often preferred in route selection to reduce traffic caused by multi-hop retransmission. Furthermore, as probability of packet delivery success in condition of route existence $P_f((L, \rho, \gamma)$ depends on the route distance as presented in (3.2), it can be improved for shorter selected routes. In order to reduce routing overhead, beside applying shortest path criterion, OLSR also relies on another technique which uses only few nodes in Multi Point Relaying (MPI) set to populate topology update information, [37]. High traffic overhead also has significant impact on the probability $P_r(L, \rho, \gamma)$ of route establishment as the topology information is prevented from travelling afar by the transmission collision in network.

The experiment of AANET over nodes distributed in an area as shown in Fig. 3.3 also produced similar results. The parameter setting of this simulation is shown in Table. 3.2.

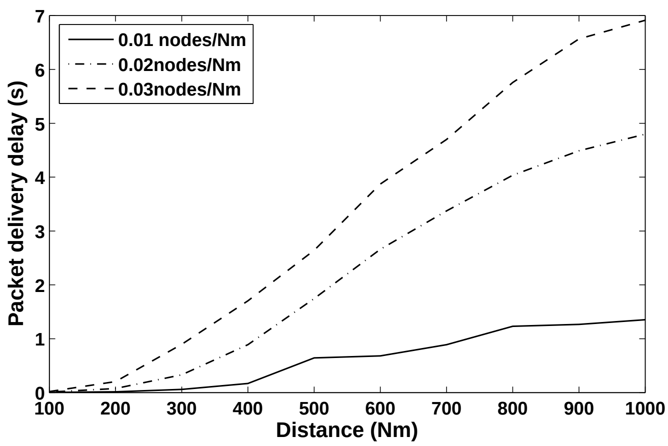
Table 3.2: Parameter setting for the simulation of AANET over nodes distributed in area

Parameter	**Value**
The width of observed area	$1000Nm$
Expected transmission range	$250Nm$
Packet sending rate of each aircraft	$2packets/s$
Packet size	$200bytes$
Node density	$10^{-5} - 5.10^{-5} nodes/Km^2$

In summary, network performances does not only depend on connectivity condition of network, but also on route stability, link reliability, and network traffic density. Network performances can be improved with proper routing mechanisms. In the next section, we proposed some routing mechanisms as solutions to improve the reliability of communication over AANET.



(a) The effect of node density on packet delivery ratio



(b) The effect of node density on packet delivery delay

Figure 3.3: AANET over nodes distributed in area.

3.3 Proposed routing mechanism

From conclusion of network performance analysis, new link longevity-based routing mechanisms were proposed to improve communication reliability based on AANET. These mechanism ia based on link longevity to reduce broadcast overhead required for update of topology and neighbors. All factors effecting on network performance such as link reliability, route stability and traffic density are considered.

Firstly, we present the proposed new link longevity estimation model, in which transmission range and link longevity with a neighbor is calculated based on the $SINR$ of signal received from that neighbor. This model uses a threshold value of signal to interference and noise ratio $SINR_t$ to locate transmission range. Therefore, using this model, nodes can handle reliability of their maintained links via handling $SINR_t$. Then, the proposed link longevity-based mechanism are presented.

3.3.1 Link longevity estimation model

3.3.1.1 Transmission range

Conventionally, transmission range is defined as the distance from the transmitter position to a point at which the transmit signal power is attenuated to a reception threshold. In this model, we define transmission range as the distance from the transmitter position to a point at which signal $SINR$ is attenuated to $SINR_t$ as $SINR$ decides the probability of packet reception success.

From (1.1), we derive (3.5) and (3.6):

$$\frac{P_{ri}}{P_t} = \left[\frac{\sqrt{G_l}\lambda}{4\pi D}\right]^2, \tag{3.5}$$

$$\frac{P_{rt}}{P_t} = \left[\frac{\sqrt{G_l}\lambda}{4\pi R}\right]^2, \tag{3.6}$$

in which,

P_t: Transmission power

P_{rt}: Threshold receiving power.

P_{ri}: Instant receiving signal power

R: Transmission range

D: Instant distance between two nodes

D is computed from position and velocity information acquired from ADS-B system. The relationships between $SINR$ and receiving power are:

$$SINR = \frac{P_{ri}}{N + I}, \tag{3.7}$$

$$SINR_t = \frac{P_{rt}}{N + I}, \tag{3.8}$$

in which, $SINR_i$ is the current receiving signal.

With the uniform distribution assumption of interference and noise in a node's vicinity, from (3.5), (3.6), (3.7), (3.8), the relationship between distance and values of $SINR$ is presented as:

$$\frac{SINR_i}{SINR_t} = \frac{P_{ri}}{P_{rt}} = \frac{R^2}{D^2}, \tag{3.9}$$

From relationship (3.9), transmission range can be calculated based on $SINR$ and distance D.

$$R = D\sqrt{\frac{SINR_i}{SINR_t}}. \tag{3.10}$$

Thus, the transmission range depends on the selected value of $SINR_t$. Low $SINR_t$ offers long transmission range, but low link reliability. Higher $SINR_t$ offers high link quality, but its shorten transmission range degrades network connectedness.

3.3.1.2 Link longevity

The demonstration of link longevity estimation model is illustrated by example of transmitting node A and receiving node B in Fig. 3.4. Position and velocity parameters of A and B at time when B receives signal from A are:

A:

$$A(x_A, y_A, z_A), \tag{3.11}$$

$$\vec{V}_A(v_{xA}, v_{yA}, v_{zA}). \tag{3.12}$$

B:

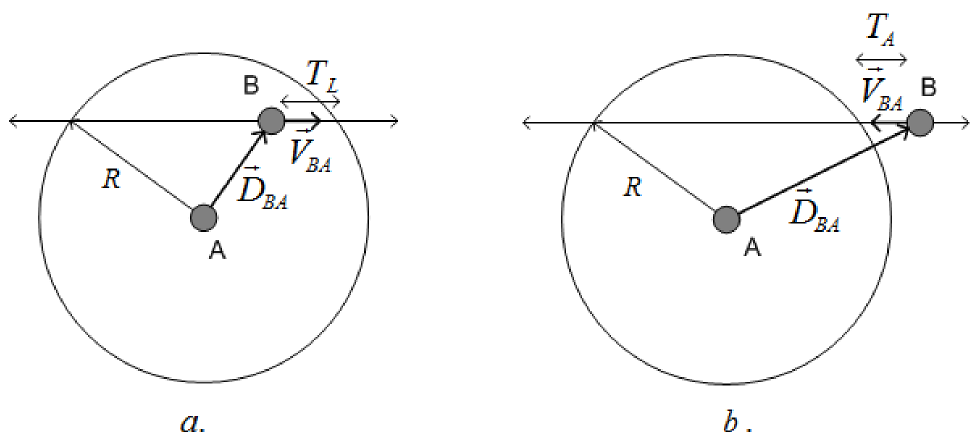


Figure 3.4: Estimation of link longevity, (a), and arrival time, (b).

$$B(x_B, y_B, z_B), \tag{3.13}$$

$$\vec{V}_B(v_{xB}, v_{yB}, v_{zB}). \tag{3.14}$$

Using $\vec{D}_{BA}$ and $\vec{V}_{BA}$ to denote the relative position and velocity of B in respective with A, we have:

$$\vec{D}_{BA}(x, y, z) = (x_B - x_A, y_B - y_A, z_B - z_A), \tag{3.15}$$

$$D_{BA} = \sqrt{x^2 + y^2 + z^2}, \tag{3.16}$$

$$\vec{V}_{BA}(v_x, v_y, v_z) = (v_{xB} - v_{xA}, v_{yB} - v_{yA}, v_{zB} - v_{zA}), \tag{3.17}$$

$$V_{BA} = \sqrt{v_x^2 + v_y^2 + v_z^2}. \tag{3.18}$$

After time t, the relative position of B to A is:

$$\vec{D_{BA_t}}(x_t, y_t, z_t) = (x + v_x t, y + v_y t, z + v_z t), \tag{3.19}$$

Longevity of link from A to B is derived from the remaining time B inside A's transmission range. It is seen as the time for B to move from its current position to A's transmission range border. That is the non-negative solution of:

$$R = D_{BA_t} = \sqrt{x_t^2 + y_t^2 + z_t^2}, \tag{3.20}$$

which corresponds to:

$$V_{BA}^2 T^2 + 2\vec{D}_{BA}\vec{V}_{BA}T + D_{BA}^2 - R^2 = 0, \tag{3.21}$$

with $\vec{D}_{BA}\vec{V}_{BA} = xv_x + yv_y + zv_z$

Nevertheless, the solution of (3.21) depends on those parameters appeared in the expression. The non-soluble case occurs when B locates outside and never move within A's transmission range. Otherwise, two solutions are found as follows:

$$T_1 = \frac{-\vec{D}_{BA}\vec{V}_{BA} + \sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2 + (R^2 - D_{BA}^2)V_{BA}^2}}{V_{BA}^2}, \tag{3.22}$$

$$T_2 = \frac{-\vec{D}_{BA}\vec{V}_{BA} - \sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2 + (R^2 - D_{BA}^2)V_{BA}^2}}{V_{BA}^2}. \tag{3.23}$$

$T_1 - T_2 = \frac{2\sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2+(R^2-D_{BA}^2)V_{BA}^2}}{V_{BA}^2}$ is the total time that B stays in A's transmission range. If the time origin is set at the current time, T_2 is the arrival time that B enters A's transmission range, and T_1 is the departure time that B leaves A's transmission range. Therefore, at the time that B locates inside A's transmission range, that means $D_{BA} < R$ as depicted in (Fig. 3.4.a), T_2 is the elapsed time since B entered and T_1 is the remaining time until B will depart from A's transmission range. Longevity T_L of the link from A to B is expressed by T_1: $T_L = T_1$. Conversely, if $D_{BA} > R$, two other possibilities can happen. The first possibility corresponds to B having left A's transmission range. It is expressed by both T_1 and T_2 being negative. This case is recognized by $\vec{D}_{BA}\vec{V}_{BA} > 0$. The second possibility is B approaching A's transmission range (Fig. 3.4.b). It is expressed by both T_1 and T_2 non-negative. This case is recognized by $\vec{D}_{BA}\vec{V}_{BA} \leq 0$. T_2 is seen as arrival time T_A that B enters A's transmission range; e.i. $T_A = T_2$. For the special case that A and B move with the same velocity; $\vec{V}_{BA} = \vec{0}$. If B is instantly inside A's transmission range, their link longevity is infinitive. Otherwise, B will never cross A's transmission range.

In summary, the link longevity prediction model is demonstrated as follows:

If $D_{BA} \leq R$

If $\vec{V}_{BA} = \vec{0}$

$$T_L = \infty. \tag{3.24}$$

Else

$$
\begin{aligned}
T_L &= \frac{-\vec{D}_{BA}\vec{V}_{BA} + \sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2 + (R^2 - D_{BA}^2)V_{BA}^2}}{V_{BA}^2} \\
&= \frac{-\vec{D}_{BA}\vec{V}_{BA} + \sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2 + (\frac{SINR_i}{SINR_t} - 1)D_{BA}^2 V_{BA}^2}}{V_{BA}^2}.
\end{aligned}
\tag{3.25}
$$

Else

If $\vec{V}_{BA} = \vec{0}$

$$T_A = \infty. \tag{3.26}$$

Else

If $\vec{D}_{BA}\vec{V}_{BA} \leq 0$

$$
\begin{aligned}
T_A &= \frac{-\vec{D}_{BA}\vec{V}_{BA} - \sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2 + (R^2 - D_{BA}^2)V_{BA}^2}}{V_{BA}^2} \\
&= \frac{-\vec{D}_{BA}\vec{V}_{BA} - \sqrt{(\vec{D}_{BA}\vec{V}_{BA})^2 + (\frac{SINR_i}{SINR_t} - 1)D_{BA}^2 V_{BA}^2}}{V_{BA}^2}.
\end{aligned}
\tag{3.27}
$$

Else

$$T_L = 0. \tag{3.28}$$

3.3.2 Neighbor management

Knowing link longevity, a node can manage the existence of links to neighbors without requirement of frequent update. In this section, we present the proposed mechanism to maintain neighbor state based on link longevity.

Two kinds of link are defined between a node and its neighbor. Reverse link is the link directed from the neighbor to this node. The forward link is the link directed from the node to its neighbor. The node receives signal from the neighbor via the reverse link and sends signal to its neighbor via the forward link. Therefore, a node can estimate longevity of only the reverse link. In order to for forward link longevity to be acquired, information exchange is necessary between two nodes. When the node does not know about forward link longevity, it set this metric as zero. According to longevity of links, the node manage its neighbors via neighbor state as follows

- ”2 Way”: this neighbor state is set when link longevity in two direction is positive.
- ”1 Way”: this neighbor state is set when reverse link longevity is positive, and forward link longevity is zero.
- ”Unstable”: this neighbor state is set when reverse link longevity is zero but the link is not expired.
- ”Loss”: this neighbor state is set when the reverse link is expired.

The reverse link is expired when the node does not receive any signal transmitted from this neighbor after maximum update time requirement since the latest update. Managing neighbor state based on link longevity can reduce the regular update rate, but the maximum update time is still needed for nodes to be still aware of the existence of each other, and the possible change occurring to the neighbor such as velocity.

When a node found a neighbor in ”Unstable” state, it set a timer for arrival time of the reverse link setup if the arrival time positively exists. When the timer is expired, it will broadcast a Hello message to advertise it presence to that neighbor.

When the neighbor state is ”1 Way”, the node broadcast a Hello message including the reverse link longevity. The purpose of this broadcast is to update the reverse link longevity to the neighbor and acquire the forward link longevity estimated by the neighbor.

When the neighbor is in ”2 Way”, the neighbor is added to the topology table, and communications transactions to the neighbor can take place since then.

During the neighbor state maintenance, the node frequently monitors reversed link longevity. It can be varied by noise and interference. When the reverse link longevity changes beyond a threshold, the node will send to the respective neighbor the update. This mechanism alleviates the update rate, while the reliability is still maintained. When link longevity is expired, the neighbor state is automatically changed according to the above regulation. The neighbor is removed from the neighbor table when it is in ”Loss” state.

3.3.3 Route dissemination

The investigated model has function to supply communication service between aircraft and the ground station. Therefore, the routing mechanism developed for this model should concentrate on routes between aircraft and the ground station only. Route dissemination mechanism that we proposed here complies with the mechanism that was proposed in [2]. The ground station information is broadcast widely over network. Aircraft unicast directly their information to the ground station. However, as the existing routing mechanism based on position to forward packet, so position and velocity instead of routes to the destinations are maintained. It requires nodes frequently broadcast information to update. In the mechanism that we proposed, the maintained route information to each destination is [Destination Address, Next Node, Hop Count, Route Longevity]. Managing routes based on route longevity limits the requirement for topology frequently update. Following is the demonstration of the route dissemination mechanism that we proposed.

3.3.3.1 Route to the ground station dissemination

The ground station periodically broadcasts its information via Hello message. The aircraft receiving the ground station information consider this information as their state information. An aircraft having route to the ground station is express by the availability of this information in its broadcasted Hello messages. When receiving the ground station information, the aircraft rebroadcast immediately only if it detects at least one of its ”2 Way” neighbors not having route to the ground station. Otherwise, the ground station information is broadcasted as schedule of that aircraft. This mechanism can limit information flooding.

Ground station information added in a Hello message includes: [Ground Station Address, Hop Count, Connection Time]. The ”Hop Count” is the route distance from the broadcast aircraft to the ground station. This metrics is modified by adding a value of one when it is delivered to a new aircraft. An aircraft can find more than one routes to the ground station by receiving ground station information from different neighbors. ”Connection Time” is the maximum longevity of its holding routes. Longevity of a route is equal to the minimum longevity of its component links. An aircraft calculates longevity of a route from it to the ground station by comparing the ”Connection Time” in the broadcast Hello message of a neighbor with longevity of link to that neighbor.

Along with ground station information, another important state information included in the Hello message is congestion status. The congestion handling mechanism is described in the later section. The route relying on the neighbor that is in congestion will be mark as congestion. The congestion time as the MAC queuing delay time is also included. Aircraft will limit forwarding data on congested routes.

An obtained route is accepted by a node if the node has no route to the ground station yet. Otherwise, regarding the issues such as possible route looping, high multi-hop retransmission traffic, congestion, and route stability, following is the regulation that the node has to comply when considering adding a new route.

A route is considered as stable when its longevity is greater than a stable threshold, and as unstable if condition is otherwise. When a node is possessing a route to the ground station, a new route is accepted if it is stable and:

- Longevity of all routes that the node is holding are unstable, otherwise
- All routes that the node is holding are congested while the new route is not congested and its distance is not longer than the existing ones, otherwise
- The new route distance must be shorter than all of the existing stable routes held by the node.

After the new route is added, every existing route that is unstable or longer is removed from the routing table.

With this regulation, each node only try to maintain the shortest stable, and uncongested routes. The unstable routes are never accepted. In normal condition, only the uncongested stable route with shorter distance than existing ones is added. In congestion condition, the route is accepted only if it is uncongested and not longer than the existing one.

In order to facilitate nodes in network to maintain the best routes to the ground station, when a node detects a neighbor which has recently broadcast the worse route than what it can offer, it will broadcast to advertise its information status to that neighbor. The conditions for a node to offer its route to the neighbor is that: The node is not in congestion status and the route that the neighbor can rely on it is stable. Besides that, the current status of the route broadcasted by that neighbor is:

- Unstable, or
- Longer than the route relying on the node, or
- In congestion.

When longevity of all routes is nearly expired that connection time of the node to the ground station is smaller than a threshold, the node frequently broadcasts until it finds a new better route. If the node loses all routes to the ground station, it will broadcast immediately to announce others about its status. By that, the neighbors whose routes relying on it can know and remove that broken route from their routing table. The route adds a new route again only after an time interval in order to avoid the problem of looping route.

3.3.3.2 Route to aircraft dissemination

When aircraft find route to the ground station, they unicast directly its information to the ground station. The ground station and other intermediate aircraft which the message passes over will know route to reach the transmitting aircraft. The rate of route unicast depends on longevity of routes from aircraft to the ground station. The unicast time interval is extended long for high longevity routes. The route to aircraft is also update when aircraft transmit data to the ground station. Employing data packet transmission, aircraft can limit route unicast to reduce unnecessary overhead.

3.3.4 Route selection

If a node has more than one routes to a destination, the node selects one route from the available ones to forward the packet. The proposed routing selection mechanism considers multi-criteria instead of single criterion as in the existing routing protocols to select route. The objective function of this mechanism is to optimize route distance:

$$H(r) = \min_{r_i \in Rt}(H(r_i)), \tag{3.29}$$

in which, $H(r)$ presents hop count distance of route r, Rt is set of available routes. The criteria for route selection are presented under constraint function as follows:

$$T(r) > t_s, \tag{3.30}$$

$$G(r) = 0, \tag{3.31}$$

$$R(r) > SINR_s, \tag{3.32}$$

in which, $T(r), G(r), R(r)$ present, respectively, the stability, the congestion status, and the reliability of route r. Route stability is measured by longevity of the route. A route r is considered as stable if it satisfies (3.30) with t_s is stability threshold. The route r is not congested if it satisfies (3.31). When $G(r) = 1$, route r is congested. Route reliability is expressed by the $SINR$ of the recently received signal on the link from the node that is the route's gateway. The route satisfying (3.32) is considered as the reliable route. These constraints are considered in priority order as being shown. The sets of routes after passing each constraint in priority order are denoted as Tr, Gr, Rr, so that $Rr \in Gr$ and $Gr \in Tr$. If $|Tr| = 0$, that means there is no route satisfying the first constraint (3.30), the link longevity optimization is applied for route selection:

$$T(r) = \max_{r_i \in Rt}(T(r_i)), \tag{3.33}$$

If $|Tr| > 0$ and $|Gr| = 0$, all stable routes are congested. When this happens, congestion time optimization is applied on Tr to select the lowest congestion time route:

$$Tg(r) = \min_{r_i \in Tr}(Tg(r_i)), \tag{3.34}$$

If $|Gr| > 0$ and $|Rr| = 0$, link reliability optimization is applied:

$$R(r) = \max_{r_i \in Gr}(R(r_i)), \tag{3.35}$$

The solution of (3.29) followed by the given constraints can be a set of routes that is denoted as Hr. If $|Hr| > 1$ while only one route is required, link reliability optimization (3.36) is applied again on Hr to obtain the unique route.

$$R(r) = \max_{r_i \in Hr}(R(r_i)), \tag{3.36}$$

Route selection mechanism presented in steps as follows:

1. The stable routes are selected from the available routes

2. If there are more than one stable route, the uncongested routes are selected from the available routes.

3. If there are more than one uncongested routes, reliable routes are selected from the found uncongested routes.

4. If there are more than one reliable routes, the shortest routes are selected from the found reliable routes.

5. If there are more than one shortest routes, the most reliable route is selected.

6. If there is no reliable route in step 3, the most reliable route is selected from the found uncongested routes.

7. If all routes in step 2 are congested, the route selected is the route have lowest congestion time.

8. If there is no stable route in step 1, the most stable route is selected from the available routes.

3.3.5 Congestion announcement and traffic handling

In the investigated model, traffic flows from all aircraft in network concentrate at the ground station. Therefore, network area around the ground station can easily get congested. The congestion announcement and traffic handling mechanism are proposed here to release network congestion. It regulates traffic to be transmitted on AANET based on network congestion status. A node can sense network congestion via long MAC transmission queueing time. Therefore, the proposed mechanism uses MAC queuing time as an indicator of network congestion status. A node considers network congested when its MAC queueing time is great beyond a certain threshold, and set itself to be in congested state. As nodes at nearer the ground station can get into congested state earlier, the persistent arrival of traffic flows from nodes in remote uncongested area will make the congestion in area around the ground station more serious. The congestion announcement is proposed to limit the arrival of remote traffic flows when the nearer area is congested. Following is the demonstration of the proposed congestion announcement and traffic handling mechanism.

A value of MAC queuing time is assigned as congestion threshold of network. The node state is in congestion if its MAC queueing time is higher than this threshold. When changing from normal to congested state, a node broadcast to update its state. When another node receives this update and has route relying on this congestion node, it will set that route state as congestion. If the MAC queuing time of a node has not yet get congestion threshold, but all of its routes the the ground station are in congestion, it also set itself as congested. When changing back to normal state, the node delays a certain time before updating its state to others to avoid congestion control traffic increasing by the oscillation between normal and congestion state. When receiving the update, other nodes also set back their routes relying on this node to normal.

A node will cease its own data transmission on AANET or switch its data transmission to another system when its state is congested. Only the transit traffic for other nodes is continued to be delivered in network. Due to the possible transmission collision, the congestion announcement message may not correctly be received by others. The congestion node will update its state again if after a certain time, it still receives transit data packets of its neighboring nodes.

3.3.6 Broadcast mechanism

Most of the routing control processes as presented above rely on Hello message broadcast. There can be many broadcast events occurring in the same time, or for long time, but there is not any broadcast event. Therefore, in order to reduce unnecessary broadcast overhead in the dense event condition or to maintain the periodical update state when no event occurs, a broadcast handling mechanism was developed.

The broadcast of a node is managed by a broadcast handler. When there is not any event, the broadcast handler schedules the periodical broadcast of the node. The time interval between broadcast depends on if the node has routes to the ground station. When the node has routes to the ground station, the time interval between broadcast t_G is much longer than the time interval t_0 when the node has no route. As nodes manage neighbor state based on link longevity, so long t_G helps reduce unnecessary update broadcast overhead, but still maintain connection status between neighbors. Shorter t_0 in condition of no route to the ground station help node sooner to acquire the route. High broadcast rate in this state does not effect much on network performance as there is no route for communication transactions between the node and the ground station.

When a event to broadcast occurs, the broadcast handler reschedules if the broadcast time of the event is sooner than the next scheduled broadcast. The interval between broadcast time is always guaranteed greater than a minimum time broadcast threshold. After each broadcast, the broadcast events between the last and the recent broadcast are removed before the broadcast for the next event is scheduled.

3.4 Conclusion

From experiment results of simulated AANET, in this chapter, we analyzed the factors affecting on network performance. Apart from network connectedness, the effect of other connectivity aspects on network performance are formulated as route stability and link reliability. From the issues analyzed, new proposed routing mechanisms to improve network performance were presented. Our derivation of the new link longevity estimation model allows aircraft to estimate link longevity dynamically with variable transmission range. The reliability of link establishment can be handled via the parameter $SINR_t$ of the model. In the next chapter, the performance of the new proposed routing mechanism is investigated.

CHAPTER IV

LINK-LONGEVITY BASED ROUTING PERFORMANCE EVALUATION

4.1 Introduction

Performances of the routing mechanisms proposed in the previous chapter were investigated via the implementation of a trial routing protocol that these mechanisms are integrated in. In this chapter, we describe this routing implementation, present experiment result and discuss new routing performance.

4.2 Routing protocol structure

The trial routing protocol is described by the block structure in Fig. 4.1. ”Route Output” and ”Rout Input” are two interface blocks, in which, ”Route Output” provides routes for data traffic transmitted by the node itself and ”Route Input” provides routes for transit traffic of other nodes. The route is selected by the ”Route Selection” block from the ”Routing table” based on the proposed route selection mechanism as described in the section 3.3.4. The ”Traffic Handler” block controls the output data traffic of the node whether to be transmitted on AANET with the selected route, or on another backup system according to node states as demonstrated in the section 3.3.5. Network topology update and maintenance are managed by the ”Topology Handler” block. It learns network topology via received routing messages from other nodes and perform the proposed route dissemination mechanism that was presented in the section 3.3.3.2. The congestion announcement presented in the section 3.3.5 is performed by the block ”Congestion Handler”. Neighbor discovery, neighbor update and maintenance are handled by the ”Neighbor Management” block with the proposed neighbor management mechanism presented in the section 3.3.2. The block ”Broadcast Handler” schedules Hello message broadcast for node periodical update and on events generated by ”Topology Handler”, ”Congestion Handler” and ”Neighbor Management” blocks.

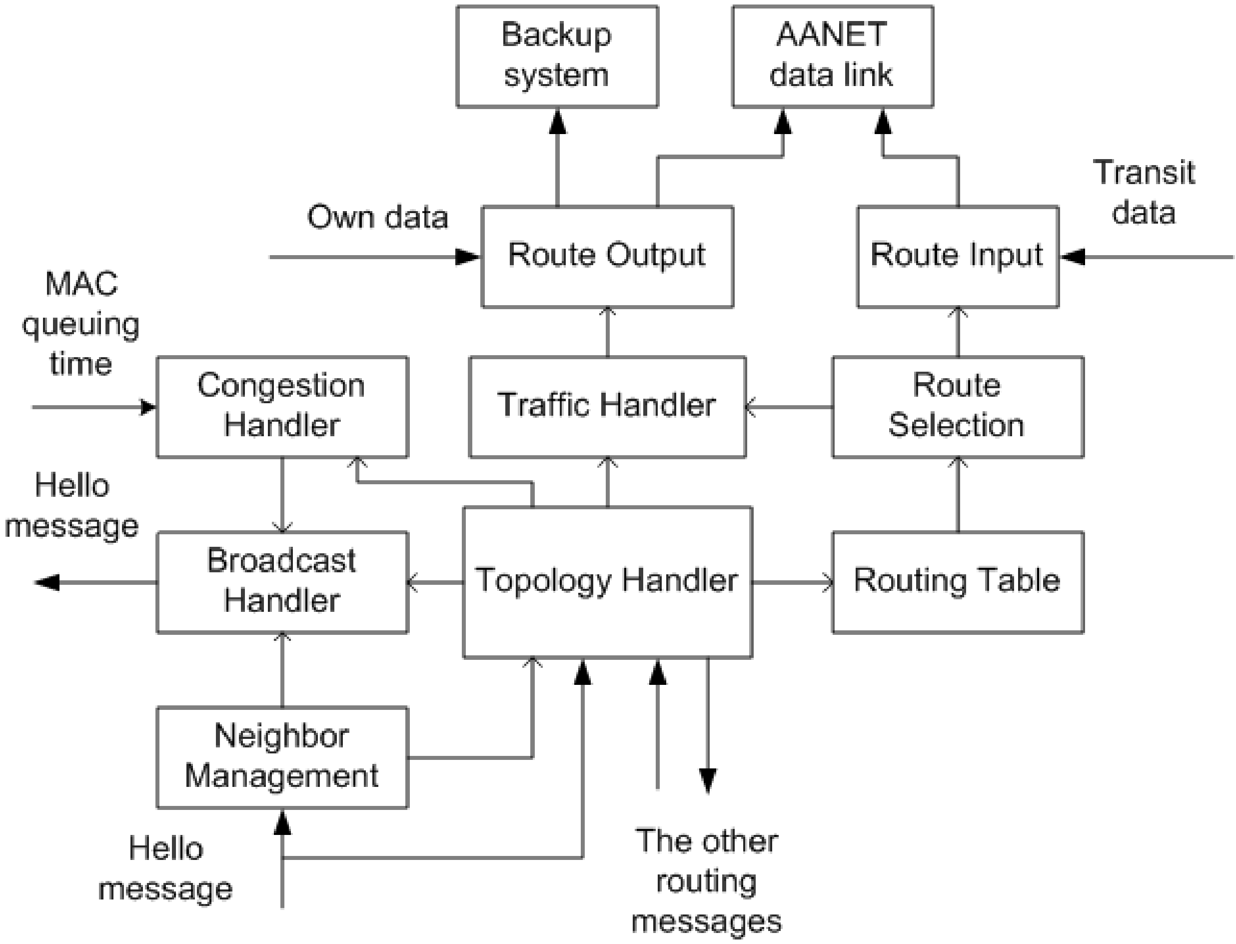


Figure 4.1: Routing protocol structure

4.3 Routing control messages

Routing control messages used by the trial routing protocols are Hello message, Aircraft Advertisement (AA) message, and Route Error (RE) message. The Hello message is used for nodes in network to broadcast their state in processes such as neighbor update, route dissemination, and congestion announcement. AA message is used by aircraft to unicast to the ground station, advertising their presence in network. When a packet is forwarded to a node that has no route to the packet's destination, RE message transmitted by the node to the recent packet forwarder to reject forwarding packet.

For the purpose of node state broadcast and local metric exchange between neighboring nodes, information included in a Hello message to broadcast is as follows:

- Node type: indicating the type of broadcast node whether it is a ground station or an aircraft.

- Congestion state : indicating whether the broadcasting node is congested.
- Information of route to a ground station: ground station address, route's gateway address, hop count, connection time. These fields are excluded if the broadcast node has no route to the ground station.
- Neighbor entry: neighbor address, reverse link longevity, forward link longevity. Neighbor entries are included in the message only for neighbors in the negotiation process.

Information carried in a AA message is hop count and longevity of the route to the original aircraft. This information is initialized as zero for hop count and infinitive for route longevity at the original aircraft. It is updated every time the message is forwarded to a node on delivery progress to the ground station: the hop count is increased one and route longevity is the minimum value in comparison between the existing route longevity contained in the message and longevity of the link between the node and the node recently forwarding the message. The nodes relaying the message also learn about the route to the original aircraft from information that it contains.

In RE messages, the rejected destination address is included. On receiving an RE message from a neighboring node, the given node will remove the unavailable route through this neighbor from its routing table.

4.4 Routing processes

4.4.1 Hello message broadcast

The event and periodical broadcast of a node is handled by the "Broadcast Handler" in the routing functional structure according to the proposed mechanism as described in the section 3.3.6. Interval time of periodical broadcast is set as follows:

- The broadcast interval time of a ground station: 2 seconds
- The broadcast interval time of an aircraft without route to the ground station: 2 seconds
- The broadcast interval time of an aircraft with route to the ground station: 30 seconds

When an event to broadcast occurs, time interval between broadcast changes upon on the event. The minimum time between two continuous broadcast is $0.1s$.

4.4.2 Neighbor discovery and maintenance

Neighbors are managed based on link longevity by the mechanism proposed in the section 3.3.2. Neighbor information is maintained in the neighbor table. Each neighbor entry is a tuple of [NA, NS, FT, RT, LRT], which are Neighbor Address, Neighbor State, Forward link expired Time, Reverse link expired Time, and Latest update Reverse link expired Time. RT is obtained from the reverse link longevity estimated based on the received signal generated by the respective neighbor. The FT is obtained from the forward link longevity sent by the neighbor through information exchange process. The NS is indicated by RT and FT as presented in the section 3.3.2. LRT is the latest value of RT that was feedback to the neighbor. The difference between LRT and RT higher than a certain threshold will trigger the information exchange to update. Following is the description of the information exchange procedure, which is illustrated between two neighboring nodes u and v.

u discovers v when it receives v's broadcast Hello message. It adds v as an entry into its neighbor table. Neighbor state NS whether of "1_WAY" or "UNSTABLE" is set to u depending on its reverse link expired time RT. If NS is 1_WAY, u starts the negotiation process by broadcasting Hello message in which the neighbor entry of v with the reverse link longevity metric is included .

If v finds its entry in u's broadcast Hello message, it adds u's entry into its neighbor table. The reverse link longevity metric contained in the message corresponds to v's respective forward link longevity. Neighbor state NS set to u as whether "2_WAY" or "UNSTABLE" depending on its reverse link expired time. If NS is 2_WAY, v replies u by enclosing u entry with reserved and forward link longevity in its next Hello message to broadcast.

When u finds its entry in that v's broadcast Hello message, u updates v's entry in the neighbor table with neighbor state NS set as "2_WAY". The negotiation process is finished if the feedback of reverse link longevity included in the message is matched with the latest RT. Otherwise, u continues the information exchange to update reverse link longevity metric. The information exchange process takes place until a node finds that all the metrics contained in the message match with metrics that it is holding.

When the negotiation is finished, u and v keep monitoring their reverse link states. The significant variance between RT and LRT will trigger the update process through information exchange similar to the process that has recently described.

In the case that v is in "UNSTABLE" state when it is firstly discovered, u will set a timer as the arrival time into v's transmission range. The timer expiration will trigger its Hello message broadcast to enable v's awareness of its existence. v will start information exchange when it is aware of u as "1_WAY" neighbor via receiving u's broadcast Hello message.

In this trial routing protocol, the interval time between two continuous Hello message broadcast of a node when in information exchange process is set as $1s$.

4.4.3 Topology update and maintenance

The dissemination of routes to nodes in network is performed as the proposed route dissemination mechanism presented in the section 3.3.3. Route to the ground station is disseminated based on Hello message broadcast. Route to aircraft is learnt via their unicast AA message and data packets sent to the ground station. Each reachable node in network is stored and maintained as an entry in a routing table. As there can be more than one route to a destination, routes contained in each entry is a list of tuples of [GA, 2-GA, HC, RL, CS, CT], which correspond to Gateway Address, 2-hop Gateway Address, Hop Count, Route Longevity, Congestion State, and Congestion Time, respectively. GA is used as the identity of a route. 2-hop Gateway Address corresponds to the gateway address of the route of the current node's gateway. [CS, CT] is only applied to routes to the ground station, which is obtained from broadcast Hello messages. The information about congestion status of network is distributed by the congestion announcement mechanism as presented in the section 3.3.5.

4.4.4 Packet forwarding

The next node to forward packet in packet delivery progress is decided hop by hop based on route selection mechanism as described in the section 3.3.4. For the data of the own node addressed to the ground station, the traffic handling mechanism presented in the section 3.3.5 is applied to control the transmission of data whether on AANET.

When a packet is forwarded to a node that route to the destination is not available, the node sends RE message to the neighbor forwarding packet to announce about its status. The neighbor on receiving RE message will remove the unavailable route from its routing table.

In the next section, we present the simulation results of the trial routing performance.

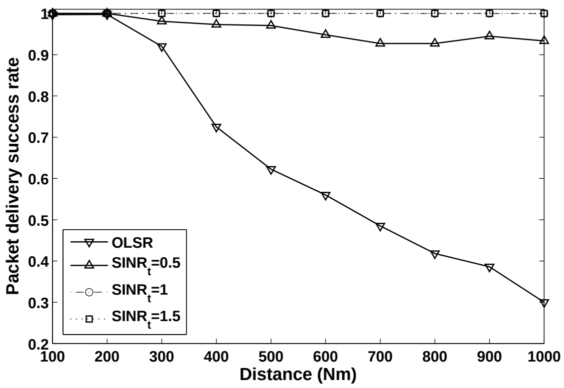
4.5 Routing experiment results

The new routing protocol was experimented in the same simulation model that was used to investigate AANET performance with OLSR routing protocol in the previous chapter. With the new routing method, data is handled to be transmitted over AANET or the backup system. The common parameters set for new routing protocol are presented in Table. 1.

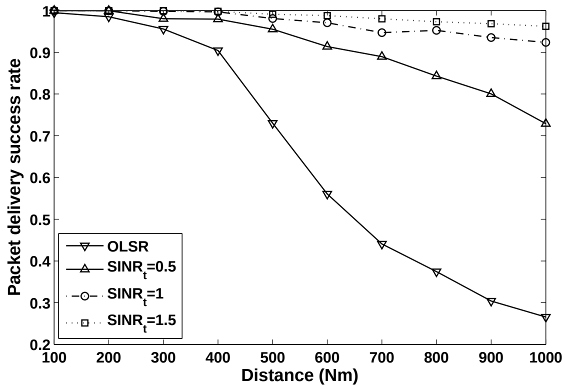
At first, we experimented the new routing protocol in AANET on a single flight path. The experiment was implemented with various node density up to $0.05 nodes/Nm$. The packet sending rate of each nodes to the ground station in this experiment was 2 packets/s. Routing performance was investigated with different values of the $SINR_t$ parameter used in the proposed link longevity estimation technique. The results were compared with network performance of the model where all sent out data is transmitted over AANET which was experimented with OLSR routing protocol. Packet delivery ratio that is the ratio of the number of received packets to the number of packets sent through AANET is denoted as ”packet delivery success rate”. Packet delivery ratio that is the ratio of the number of received packets to the total number of packets demanded to be sent is expressed for ”network efficiency”. The higher packet delivery success rate is, the more reliable network will be. As experiment results presented in the Fig. 4.2, packet delivery success rate is very high for the new routing technique. The packet delivery success rate increases with the increase of $SINR_t$.

In Fig. 4.3, network efficiency is presented. With $SINR_t = 0.5$, which gave the transmission range approximate to the one constrained by the reception sensitivity in this experiment, the network efficiency obtained by the new routing method is close to the one with the old routing method in the case of low node density as $0.01 nodes/Nm$, Fig. 4.3.(a). In low node density condition, network efficiency is low when $SINR_t$ is high. However, in high node density condition as expressed in Fig. 4.3 (b),(c), network efficiency with higher $SINR_t$ becomes higher. This is an advantage of the new routing technique as packets are delivered with high success rate without the degradation of network efficiency. Another advantage shown in Fig. 4.4 is that the packet delivery delay with the new routing method is much lower.

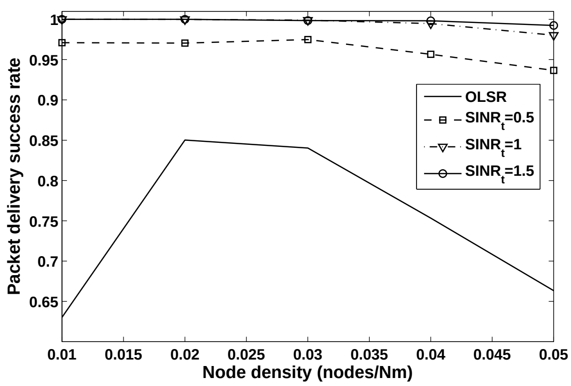
Secondly, we experimented network over nodes distributed in an area. As shown in Fig. 4.5, 4.6, and 4.7, the trend of obtained results are similar to the case of flight path-based network. In the next section, we analyzed the effect of the new proposed routing mechanisms



(a) Packet delivery rate with node density of 0.01 nodes/Nm

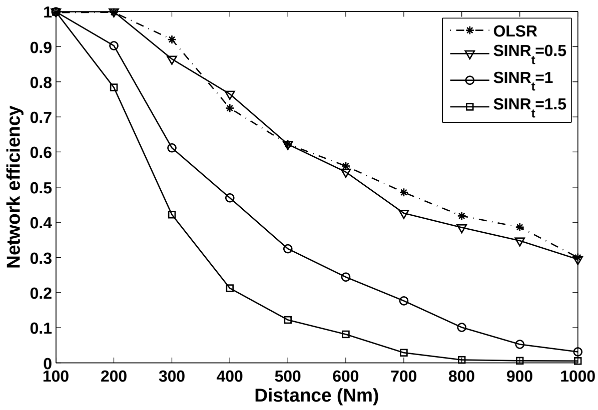


(b) Packet delivery rate with node density of 0.05 nodes/Nm

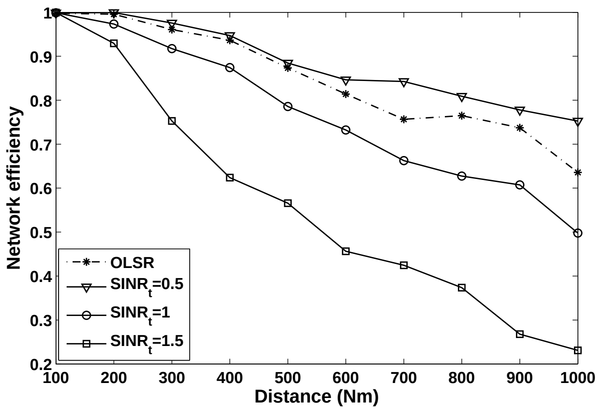


(c) The effect of node density on packet delivery success rate

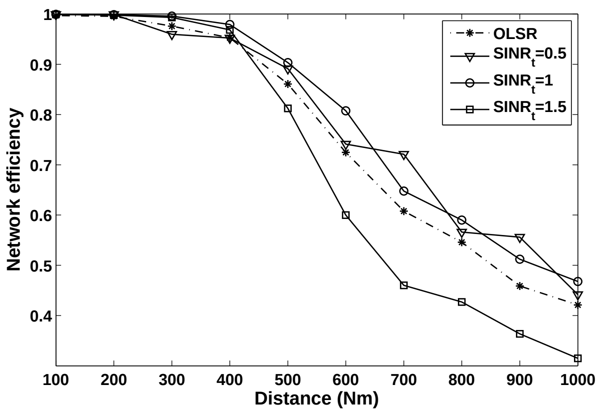
Figure 4.2: Packet delivery success rate.



(a) Density of 0.01 nodes/Nm

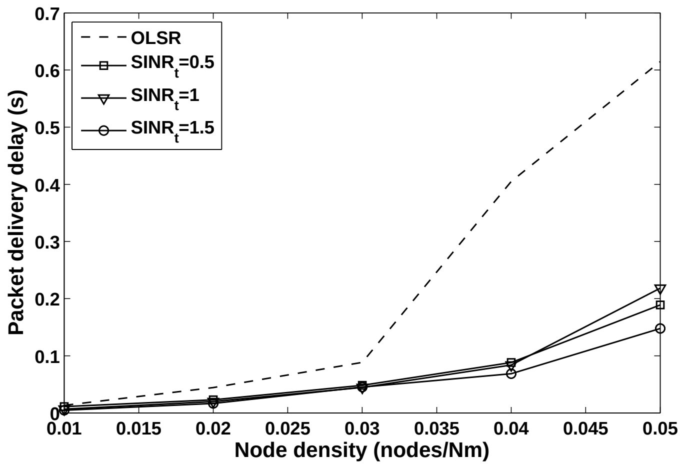


(b) Density of 0.02 nodes/Nm

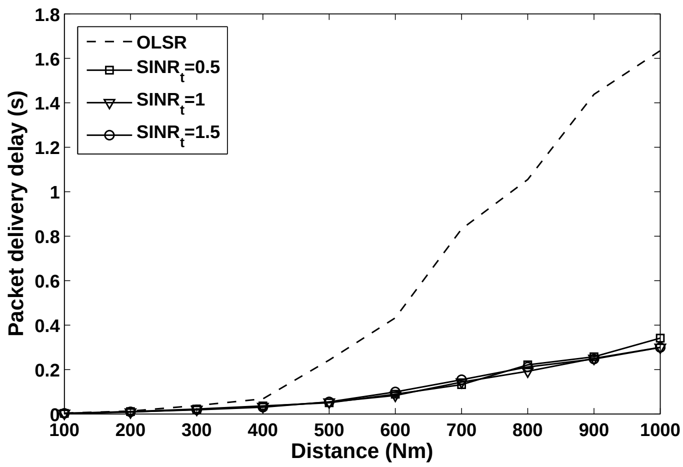


(c) Density of 0.04 nodes/Nm

Figure 4.3: The effect of node density on network efficiency with various $SINR_t$.

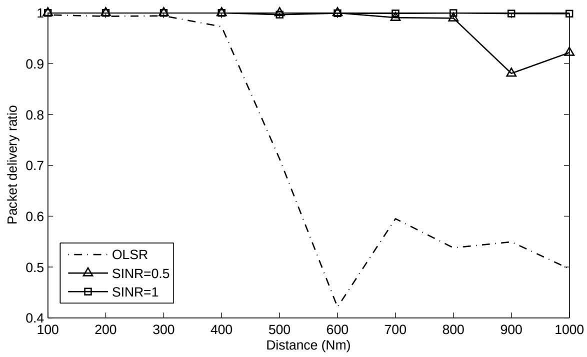


(a) The effect of node density on packet delivery delay

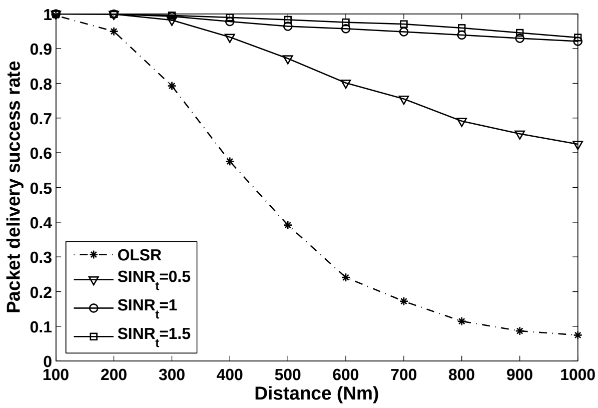


(b) The effect of distance on packet delivery delay

Figure 4.4: Packet delivery delay is much shorter with new routing methods.



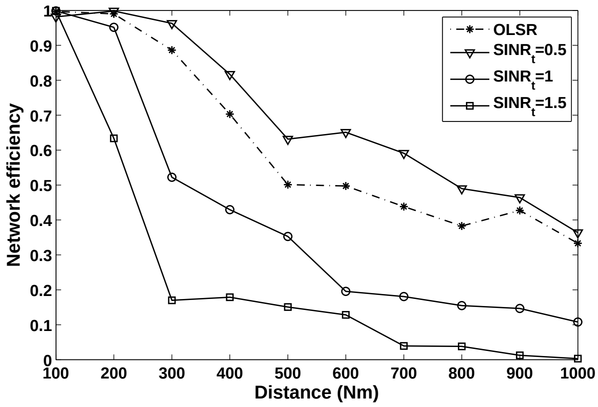
(a) Density of 0.01 nodes/Nm



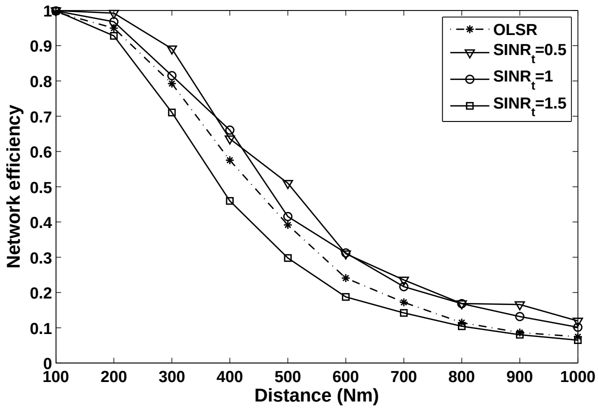
(b) Density of 0.03 nodes/Nm

Figure 4.5: Packet delivery rate in scenario of node distributed in an area.

on the network performances.

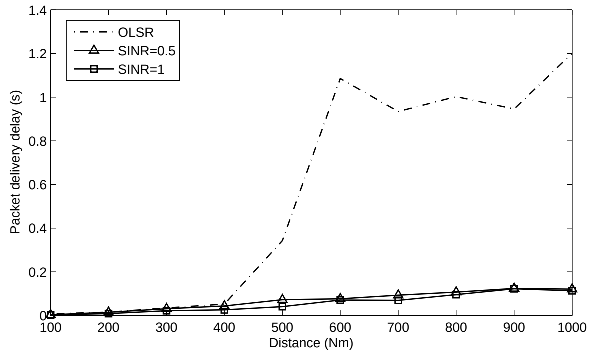


(a) Density of 0.01 nodes/Nm

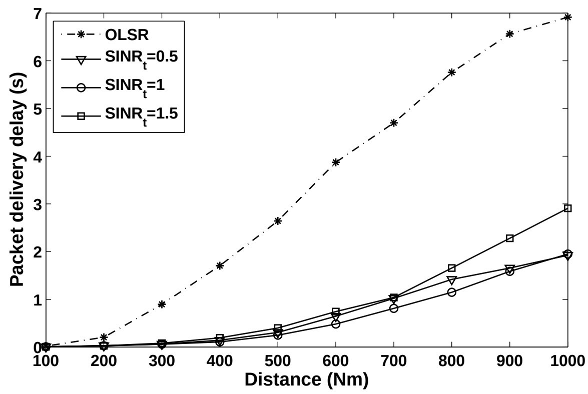


(b) Density of 0.03 nodes/Nm

Figure 4.6: Network efficiency in scenario of node distributed in an area.



(a) Density of 0.01 nodes/Nm



(b) Density of 0.03 nodes/Nm

Figure 4.7: Packet delivery delay in scenario of node distributed in an area.

4.6 Routing performance analysis

We analyzed new routing performances based on (3.1), (3.3) and (3.4). For the dependence of network performance on $SINR_t$, network efficiency is presented as follows:

$$\begin{aligned} P_{ef}(L,\rho,\gamma,SINR_t) &= P_c(L,\rho|SINR_t)P_r(L,\rho,\gamma|SINR_t)P_f(L,\rho,\gamma|SINR_t) \\ &= P_c(L,\rho|SINR_t)P_r(L,\rho,\gamma|SINR_t)\prod_{i=1}^{h(L)} A_i(\rho,\gamma|SINR_t)B_i(\rho,\gamma|SINR_t), \end{aligned} \tag{4.1}$$

in which:

$P_c(L,\rho|SINR_t)$ is the connectedness probability with the given $SINR_t$.

$P_r(L,\rho,\gamma|SINR_t)$ is the probability of at least one uncongested route to be established between the source and the destination in condition that they are connected and given $SINR_t$

$P_f((L,\rho,\gamma|SINR_t)$ is the probability of packet delivery success from the source to the destination in condition of route existence and the given $SINR_t$.

$A_i(\rho,\gamma|SINR_t)$ is the link availability at hop i^{th}, which is the probability of link existence when packet is delivered at hop i^{th}, with the given $SINR_t$ condition.

$B_i(\rho,\gamma|SINR_t)$ is the link reliability at hop i^{th}, which is the probability of packet delivered successful at hop i^{th} in the condition of link available and $SINR_t$ given.

As packet delivery success rate refers to only packets that are really sent through AANET, it is considered as the probability of packet delivery success when route is available:

$$\begin{aligned} P_s(L,\rho,\gamma,SINR_t) &= P_f(L,\rho,\gamma|SINR_t) \\ &= \prod_{i=1}^{h(L)} A_i(\rho,\gamma|SINR_t)B_i(\rho,\gamma|SINR_t), \end{aligned} \tag{4.2}$$

$B_i(\rho,\gamma|SINR_t)$ is high when $SNIR_t$ is high. Therefore, from (4.2), packet delivery success rate is increased when $SINR_t$ is increased.

Low $SINR_t$ can improve connectedness probability $P_c(L,\rho|SINR_t)$ as it offers large transmission range. Furthermore, with large transmission range, link longevity is taken longer, increasing the link availability $A_i(\rho,\gamma|SINR_t)$. The new routing method bases on both route stability, link reliability, and route hop count as criteria for route selection. The reliability criteria can enhance $B_i(\rho, \gamma|SINR_t)$ even though $SINR_t$ is low. As a result, packet delivery success rate is high while network efficiency can be still maintained or higher with the new routing technique.

However, high connectedness probability is also a reason of high interference in the network as more nodes are enabled for transmission. High interference condition can degrade transmission range to maintain $SINR_t$. $B_i(\rho, \gamma|SINR_t)$ as a result is reduced because the number of routes with reliable links is limited. Therefore, packet delivery success rate of the low $SINR_t$ is always lower than high $SINR_t$, especially in high node density condition.

For high $SINR_t$, the minimum requirement of link reliability $B_i(\rho, \gamma|SINR_t)$ is achieved. However, high interference in high node density condition makes decreasing transmission range. It adversely affects link availability $A_i(\rho, \gamma|SINR_t)$, which is already decreased by high $SINR_t$. Therefore, in spite of high $SINR_t$, packet delivery success rate is also decreased when node density increases.

$A_i(\rho, \gamma|SINR_t)$ and $B_i(\rho, \gamma|SINR_t)$ are also affected by the traffic handling mechanism. As the traffic handling mechanism in the proposed routing method can regulate traffic transmission in network, the serious impact of high interference on these probability components can be reduced. That helps guarantee the reliability for packet delivery as short delay and high success rate.

As presented in (4.1), network efficiency is always smaller than the connectedness probability $P_c(L, \rho|SINR_t)$ as it does not depend only on the connectedness probability. In low node density condition, the interference is not too high to degrade the other probability components. Therefore, higher connectedness probability as a result of lower $SINR_t$ makes network efficiency increased. However, in high node density condition, network efficiency is decided by the existence probability of uncongested routes $P_r(L, \rho, \gamma|SINR_t)$. $P_r(L, \rho, \gamma|SINR_t)$ is decreased when $SINR_t$ decreases as a result of the increase of traffic by transmission of more connected nodes in the network. Thus, with high $P_r(L, \rho, \gamma|SINR_t)$ and $P_s(L, \rho, \gamma|SINR_t)$, sufficiently high $SINR_t$ can offer high network efficiency in high node density condition.

4.7 Message complexity

Routes from the ground station to aircraft is established based on AA message unicast from aircraft. In the worst case, AA message of an aircraft has to be relayed by all of the remaining aircraft in the network. In that case, the total number of transmission and retransmission of AA messages for routes from all aircraft to the ground station is $\frac{N(N+1)}{2}$. N is the number of aircraft in network. Therefore, the complexity of route establishment is denoted as $O(N^2)$. The route from aircraft to the ground station based on local Hello message broadcast only, so its complexity is $O(N)$. The total message complexity for route establishment of the new routing mechanisms is $O(N) + O(N^2)$. Besides relying on local Hello message broadcast, $OLSR$ routing also bases on universal broadcast of topology messages over network. In the worst case, the topology message of a node is rebroadcasted by all remaining nodes in the network. Therefore, the complexity of OLSR is $O(N) + O(N^2)$. Although the new routing method and the conventional OLSR have the same message complexity presentation, the coefficient of the new routing method depends on $SINR_t$. Because link longevity is smaller for the higher $SINR_t$, it makes routing messages transmitted with higher rate. The coefficient of the new routing method for the higher $SINR_t$ as a result is higher. The high overhead caused by high $SINR_t$ in high node density condition can make network quickly get congested. When $SINR_t$ is both lower or higher than a certain value, it can make $P_r(L, \rho, \gamma|SINR_t)$ decreased. As high $SINR_t$ is always required for high packet delivery success rate, it may lead to the trade off between the packet delivery success rate and the network efficiency.

4.8 Discussion over possible future improvements

Because the update rate is decreased with link longevity-based routing technique, the sudden change may not be timely detected. Therefore, the proposed routing mechanism is suitable for AANET of enroute aircraft that have stable mobility.

In order to reduce routing overhead, the Hello messages have to carry more node state information. That makes them take longer, decreasing the probability of message reception success.

Furthermore, the constraint of $SINR_t$ can reduce the chance for nodes to be connected while they can still receive successfully packets from each other.

Another point is that $SINR_t$ need to be set properly according to node density conditions in order for the best network performance to be achieved.

4.9 Conclusion

The performance of new routing mechanisms are achieved as expected as it can establish high reliable routes in network, which offer high packet delivery success probability and short delay. Meanwhile, high network efficiency can also be achieved with suitable value set for the parameter $SINR_t$ of the proposed link longevity estimation model.

CHAPTER V

CONCLUSION

In this dissertation, we studied connectivity and routing mechanisms of AANET. Through this research, we achieved some important contributions. Firstly, we derived the precise connectivity analytical modeling for general one dimensional network. This model can exhibit the dependence of connectedness probability on any node distribution along a network. Therefore, it can be used to evaluate connectivity in various one dimensional networks if its node distribution is known. Applying this model, connectivity analytical model of flight-path based AANET with Poisson distribution assumption of aircraft on flight path is derived. The dependence of connectedness probability on various system parameters such as the number of neighboring nodes, node density, transmission range, node velocities, and node arrival rate from two ends of the flight path is also presented with this model. The extension capability of AANET that is expressed as the network coverage extension factor for each connectedness probability requirement was also derived. This is a helpful utility in network design for AANETs.

After network connectivity modeling analysis, we formulated the effect of connectivity on network performance. The effect of node density on connectivity and packet delivery ratio was shown. The novel routing mechanisms based on link longevity were proposed to improve the reliability of network. When proposing longevity-based routing mechanism, we also derived the new link longevity estimation model that can calculate longevity of link between nodes in 3D space without transmission range knowledge requirement as in the existing model. Applying this model, network reliability performance can also be handled based on parameter $SINR_t$.

Through experiment results of the trial routing protocol that integrates all of the proposed routing mechanisms, network performance is obtained as expected. Network reliability can be handled based on the selected value of the threshold $SINR_t$. The network can achieve the best performance when proper value of $SINR_t$ is set. Due to the traffic handling mechanism in combination with the congestion announcement mechanism, the congestion problem in network in high node density is alleviated, that helps reducing delay of packet delivery in network and improve network reliability as well as efficiency.

References

[1] Sakhaee, E. and Jamalipour, A. The Global In-Flight Internet. Selected Areas in Communications, IEEE Journal on 24 (sept. 2006): 1748 -1757.

[2] Medina, D., Hoffmann, F., Ayaz, S., and Rokitansky, C.-H., Feasibility of an Aeronautical Mobile Ad Hoc Network Over the North Atlantic Corridor. Sensor, Mesh and Ad Hoc Communications and Networks, 2008. SECON '08. 5th Annual IEEE Communications Society Conference on (jun. 2008): 109 -116.

[3] Tu, H. and Shimamoto, S. Mobile Ad-Hoc Network Based Relaying Data System for Oceanic Flight Routes in Aeronautical Communications. International Journal of Computer Networks and Communications (IJCNC) 1 , 1,2009.

[4] Cheng, M. and Zhao, Y. Connectivity of Ad-hoc Networks for Advanced Air Traffic Management. Journal of Aerospace Computing, Information, and Communication 1 , 5 (2004): 225–238.

[5] Karras, K., Kyritsis, T., Amirfeiz, M., and Baiotti, S., Aeronautical Mobile Ad Hoc Networks. Wireless Conference, 2008. EW 2008. 14th European (jun. 2008): 1 -6.

[6] Medina, D., Hoffmann, F., Ayaz, S., and Rokitansky, C.-H., Topology characterization of high density airspace aeronautical ad hoc networks. Mobile Ad Hoc and Sensor Systems, 2008. MASS 2008. 5th IEEE International Conference on (sept. 2008): 295 -304.

[7] Li, H., Yang, B., Chen, C., and Guan, X., Connectivity of Aeronautical Ad hoc Networks. GLOBECOM Workshops (GC Wkshps), 2010 IEEE (dec. 2010): 1788 -1792.

[8] Bettstetter, C. and Hartmann, C. Connectivity of wireless multihop networks in a shadow fading environment. Wireless Networks 11 , 5 (2005): 579.

[9] Perur, S. and Iyer, S., Characterization of a Connectivity Measure for Sparse Wireless Multi-hop Networks. Distributed Computing Systems Workshops, 2006. ICDCS Workshops 2006. 26th IEEE International Conference on (jul. 2006): 80 - 80.

[10] Wan, P. and Yi, C., Asymptotic critical transmission radius and critical neighbor number for k-connectivity in wireless ad hoc networks. Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing, ACM, (2004): 1–8.

[11] Santi, P. The critical transmitting range for connectivity in mobile ad hoc networks. IEEE Transactions on Mobile Computing (2005): 310–317.

[12] Santi, P. and Blough, D. The critical transmitting range for connectivity in sparse wireless ad hoc networks. Mobile Computing, IEEE Transactions on 2 (jan.-march 2003): 25 - 39.

[13] Zhang, H. and Hou, J. Asymptotic critical total power for k-connectivity of wireless networks. IEEE/ACM Transactions on Networking (TON) 16 , 2 (2008): 347–358.

[14] Ghasemi, A. and Nader-Esfahani, S. Exact probability of connectivity one-dimensional ad hoc wireless networks. Communications Letters, IEEE 10 (apr. 2006): 251 - 253.

[15] Noshiro, A., Yoshikawa, T., and Kurihara, M. Analysis of Connectedness of the Fixed Radius Random Graph Model in One-dimensional Space. Soft Computing as Transdisciplinary Science and Technology (2005): 1288–1296.

[16] Noshiro, A. and Kurihara, M., Closed Form Solutions for Connectivity of Fixed Radius Random Graphs in One-Dimensional Space. Systems, Man and Cybernetics, 2006. SMC '06. IEEE International Conference on 4 (oct. 2006): 2939 -2943.

[17] Desai, M. and Manjunath, D. On the connectivity in finite ad hoc networks. Communications Letters, IEEE 6 (oct. 2002): 437 - 439.

[18] Gore, A. Correction to "Comments on 'On the connectivity in finite ad hoc networks'". Communications Letters, IEEE 10 (may. 2006): 359.

[19] Li, J., Andrew, L., Foh, C. H., Zukerman, M., and Neuts, M. Meeting connectivity requirements in a wireless multihop network. Communications Letters, IEEE 10 (jan. 2006): 19 - 21.

[20] Foh, C. H. and Lee, B. S., A closed form network connectivity formula one-dimensional MANETs. 6 (jun. 2004): 3739 - 3742 Vol.6.

[21] Behnad, A. and Nader-Esfahani, S. Probability of Node to Base Station Connectivity in One-Dimensional Ad Hoc Networks. Communications Letters, IEEE 14 (jul. 2010): 650 -652.

[22] Dousse, O., Thiran, P., and Hasler, M., Connectivity in ad-hoc and hybrid networks. INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE 2 (2002): 1079 - 1088 vol.2.

[23] Khabazian, M. and Ali, M. A Performance Modeling of Connectivity in Vehicular Ad Hoc Networks. Vehicular Technology, IEEE Transactions on 57 (jul. 2008): 2440 - 2450.

[24] Yousefi, S., Altman, E., El-Azouzi, R., and Fathy, M. Analytical Model for Connectivity in Vehicular Ad Hoc Networks. Vehicular Technology, IEEE Transactions on 57 (nov. 2008): 3341 -3356.

[25] Seo, D.-W., Kim, S.-H., and Suh, Y.-J., System integration of GPSR and ADS-B for aeronautical ad hoc networks. Military Communications Conference, 2008. MILCOM 2008. IEEE (nov. 2008): 1 -6.

[26] 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. Fifth International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Citeseer.

[27] Perkins, C., Belding-Royer, E., Das, S., *et al.* Ad hoc on-demand distance vector (AODV) routing.

[28] Ogier, R., Templin, F., and Lewis, M., Topology dissemination based on reverse-path forwarding (TBRPF). tech. rep., RFC Editor, 2004.

[29] Samar, P. and Wicker, S. Link Dynamics and Protocol Design in a Multihop Mobile Environment. Mobile Computing, IEEE Transactions on 5 (sept. 2006): 1156 -1172.

[30] Hoffmann, F. and Medina, D., Protocol architecture analysis for Internet connectivity in aeronautical ad hoc networks. Digital Avionics Systems Conference (DASC), 2010 IEEE/AIAA 29th (2010): 3.C.4-1 -3.C.4-12.

[31] Karras, K., Yannis, D., Iordanakis, M., Bogdos, G., Dilintas, G., Amirfeiz, M., and Colangelo, G., Multiple Terminal Management in Mobile Ad Hoc Networks. 3 rd International Conference on Mobile Computing and Ubiquitous Networking.

[32] Van, T. T. H., Tu, H. D., and Shimamoto, S., Air traffic control communication system employing high altitude platform station (HAPS). Integrated Communications, Navigation and Surveilance Conference (ICNS), 2011 (may 2011): H5-1 -H5-9.

[33] Wang, Y. and Zhao, Y., Fundamental issues in systematic design of airborne networks for aviation. Aerospace Conference, 2006 IEEE, IEEE, (2006): 8–pp.

[34] Hoffmann, F., Medina, D., and Wolisz, A., Two-step delay based Internet gateway selection scheme for aeronautical ad hoc networks. Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on (2009): 2638 - 2642.

[35] Goldsmith, A. Wireless communications. Cambridge Univ Pr, 2005.

[36] Rappaport, T. *et al.* Wireless communications: principles and practice, vol. 207. Prentice Hall PTR New Jersey, 1996.

[37] Clausen, T., Jacquet, P., Adjih, C., Laouiti, A., Minet, P., Muhlethaler, P., Qayyum, A., and Viennot, L. Optimized link state routing protocol (OLSR).

Appendices

Appendix A

Coverage extension derivation method

We have:

$$P_c(\alpha, \beta_0) = p_0. \tag{1}$$

On the other hand, from (2.15), we also have:

$$P_c(\alpha, \lceil\beta_0\rceil) \leq P_c(\alpha, \beta_0) \leq P_c(\alpha, \lfloor\beta_0\rfloor) \tag{2}$$

$$P_c(\alpha, \lfloor\beta_0\rfloor) = \left[\tfrac{1-(1+\alpha)e^{-\alpha}}{(1-e^{-\alpha})}\right]^{\lfloor\beta_0\rfloor-1} \times \big(1 - e^{-\alpha}\big). \tag{3}$$

$$\begin{aligned} P\{C(n_a, n_b)\} = &\left(\frac{1-e^{-\rho R} - \rho R e^{-\rho R}}{(1-e^{-\rho R})}\right)^{\lfloor \frac{L}{R}\rfloor-1} \\ &\times \big(1 - e^{-\rho R} - \rho(L - \lfloor\frac{L}{R}\rfloor)e^{-\rho R}\big). \end{aligned} \tag{4}$$

Therefore:

$$\begin{aligned} &\left[\frac{1-(1+\alpha)e^{-\alpha}}{(1-e^{-\alpha})}\right]^{\lceil\beta_0\rceil-1} \times \big(1 - e^{-\alpha}\big) \leq p_0 \\ &\leq \left[\frac{1-(1+\alpha)e^{-\alpha}}{(1-e^{-\alpha})}\right]^{\lfloor\beta_0\rfloor-1} \times \big(1 - e^{-\alpha}\big) \end{aligned} \tag{5}$$

$$\lfloor\beta_0\rfloor \leq \frac{\ln\frac{p_0}{1-e^{-\alpha}}}{\ln\frac{1-(1+\alpha)e^{-\alpha}}{1-e^{-\alpha}}} + 1 \tag{6}$$

$$\lceil\beta_0\rceil \geq \frac{\ln\frac{p_0}{1-e^{-\alpha}}}{\ln\frac{1-(1+\alpha)e^{-\alpha}}{1-e^{-\alpha}}} + 1. \tag{7}$$

Assigning:

$$\beta_t = \frac{\ln\frac{p_0}{1-e^{-\alpha}}}{\ln\frac{1-(1+\alpha)e^{-\alpha}}{1-e^{-\alpha}}} + 1, \tag{8}$$

we have:

$$\lfloor\beta_0\rfloor = \lfloor\beta_t\rfloor. \tag{9}$$

Replacing (9) into (1) and combining with (2.15):

$$\left[\frac{1-(1+\alpha)e^{-\alpha}}{(1-e^{-\alpha})}\right]^{\lfloor\beta_t\rfloor-1} \times \big(1 - (1 + \alpha(\beta_0 - \lfloor\beta_t\rfloor))e^{-\alpha}\big) = p_0, \tag{10}$$

$$\beta_0 = \lfloor\beta_t\rfloor + \frac{1}{\alpha}\left[\left(1 - p_0\left(\frac{1-e^{-\alpha}}{1-(1+\alpha)e^{-\alpha}}\right)^{\lfloor\beta_t\rfloor-1}\right)e^{\alpha} - 1\right]. \tag{11}$$

Appendix B

Parameter setting for link longevity based routing

Table 1: Parameter setting for link longevity based routing

Parameter	Value
Periodical broadcast interval of a ground station	2s
Periodical broadcast interval of an aircraft when it has no route to the ground station	2s
Periodical broadcast interval of an aircraft when it has routes to the ground station	30s
Broadcast interval of an aircraft in process of neighbor information exchange	1s
Minimum broadcast interval	0.1 s
Route stability threshold	60 s
MAC queueing time congestion threshold	0.3 s

Appendix C

List of Publications

Nguyen Thi Xuan My, Yoshikazu Miyanaga, and Chaiyachet Saivichit,

”Performance Analysis for Total Delay and Total Packet Loss Rate in 802.11 MAC Layer,” Proceedings : APSIPA ASC 2009 : Asia-Pacific Signal and Information Processing Association, 2009 Annual Summit and Conference: 791-796

”Connectivity analytical modelling for a single flight path ad hoc aeronautical network,” Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON), 2010 International Conference, 19-21 May 2010, Page(s): 51 - 55

”Connectivity Modeling Analysis in Flight-Path Based Aviation Ad Hoc Networks,” New Generation Mobile and Sensor Networking and Future Networks, IEICE TRANS. COMMUN., VOL.E94B, NO.6 June 2011

”Link longevity-based routing mechanisms for Aviation Ad Hoc network,” IEEE CAMAD, 2011

Biography

Nguyen Thi Xuan My was born in 1978 in Hanoi, Vietnam. She received the Bachelor of Engineering from Hanoi University of Technology, Hanoi, Vietnam, in 2001, and the Master of Science in Electrical and Computer Engineering from Hanoi University of Technology, in 2006. She has been pursuing the Doctoral degree in Electrical Engineering at Chulalongkorn University, Bangkok, Thailand, since 2008. Her research interests include Ad hoc Networks, Aviation Networks, and Routing protocols.