UNIVERSITI PUTRA MALAYSIA

PERFORMANCE ANALYSIS OF SWARM INTELLIGENCE-BASED ROUTING PROTOCOL FOR MOBILE AD HOC NETWORK AND WIRELESS MESH NETWORKS

AYYOUB AKBARI MOGHANJOUGHI

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By

AYYOUB AKBARI MOGHANJOUGHI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

September 2009

To my wonderful parents, Jamal & Saadat

...who have raised and encourage me to be the person I am today

To my lovely Sisters, Maryam and Shabnam

...for all the unconditional love, guidance, and support

To my Kindest wife, Atefeh

...in all love, humility, and gratitude

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Chairman: Associate Professor Sabira Khatun, PhD
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Ant colonies reside in social insect societies and maintain distributed systems that present a highly structured social organization despite of the simplicity of their individuals. Ants' algorithm belongs to the Swarm Intelligence (SI), which is proposed to find the shortest path. Among various works inspired by ant colonies, the Ant Colony Optimization (ACO) metaheuristic algorithms are the most successful and popular, e.g., AntNet, Multiple Ant Colony Optimization (MACO) and AntHocNet. But there are several shortcomings including the freezing problem of the optimum path, traffic engineering, and to link failure due to nodes mobility in wireless mobile networks.

The metaheuristic and distributed route discovery for data load management in Wireless Mesh Networks (WMNs) and Mobile Ad-hoc Network (MANET) are fundamental targets of this study. Also the main aim of this research is to solve the freezing problem during optimum as well as sub-optimum path discovery process. In this research, Intelligent AntNet based Routing Algorithm (IANRA) is presented for routing in WMNs and MANET to find optimum and near-optimum paths for data packet routing. In IANRA, a source node reactively sets up a path to a destination node at the beginning of each communication. This procedure uses ant-like agents to discover optimum and alternative paths. The fundamental point in IANRA is to find optimum and sub-optimum routes by the capability of breeding of ants. This ability is continuation of route that was produced by the parent ants. The new generations of ants inherit identifier of their family, the generation number, and the routing information that their parents get during their routing procedure. By this procedure, IANRA is able to prevent some of the existing difficulties in AntNet, MACO and Ad hoc On Demand Distance Vector (AODV) routing algorithms.

OMNeT++ was used to simulate the IARNA algorithm for WMNs and MANET. The results show that the IANRA routing algorithm improved the data packet delivery ratio for both WMNs and MANET. Besides, it is able to decrease average end-to-end packet delay compared to other algorithms by showing its efficiency.

IANRA has decreased average end-to-end packet delay by 31.16%, 58.20% and 48.40% in MANET scenario 52.86%, 64.52% and 62.86% by increasing packet generation rate in WMNs compared to AntHocNet, AODV and B-AntNet routing algorithms respectively with increased network load. On the other hand, IANRA shows the packet delivery ratio of 91.96% and 82.77% in MANET, 97.31% and 92.25% in WMNs for low (1 packet/s) and high (20 packet/s) data load respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master of Sains

ANALISIS PRESTASI KECERDASAH KAWANAN BERASASHAH PROTOKOL PENGHALAAH UNTUK RANGKAIAN AD HOC MUDAH ALIH DAN JEJARING TANPA WAYAR

Oleh

AYYOUB AKBARI MOGHANJOUGHI

September 2009

Pengerusi: Profesor Madya Sabira Khatun, PhD
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Koloni semut terdapat dalam masyarakat sosial serangga dan mengekalkan sistem teragih di mana ia mengetengahkan sebuah organisasi yang berstruktur tinggi walaupun mengamalkan kesederhanaan secara individunya. Algoritma semut hasil adalah di kalangan Kecerdasan Kawanan (SI), di mana ia mencadangkan laluan yang paling singkat. Antara teknik-teknik yang diilhamkan dari koloni semut ini, algoritma metaheuristik Pengoptimuman Koloni Semut (ACO) adalah yang paling berjaya dan digemari, contohnya AntNet, Pengoptimuman Koloni Semut Pelbagai (MACO) dan AntHocNet. Namun terdapat beberapa kelemahan termasuk masalah penyejukbekuan terhadap laluan optimum, imbangan muatan, dan untuk menyambung pautan terputus disebabkah oleh pergerakan nod dalam rangkaian mudah alih tanpa wayar.

Penemuan hala yang metaherustik dan teragih untuk imbangan muatan dalam Rangkaian Jejaring Wayarles (WMN) dan Rangkaian Ad-hoc Mudah Alih (MANET) adalah tumpuan utama dalam kajian ini. Juga tumpuan utama kajian ini adalah untuk

menyelesaikan masalah penyejukbekuan semasa pengoptimuman serta proses penemuan hala yang sub-optimum. Dalam kajian ini, Algoritma Penghalaan berasaskan AntNet Cerdik (IANRA) telah dilaksanakan bagi penghalaan dalam WMN dan MANET untuk mencari halaan yang optimum dan menghampiri optimum bagi penghalaan paket data. Dalam IANRA satu nod sumber membina laluan ke nod destinasi secara reaktifnya pada permulaan setiap komunikasi. Prosedur ini menggunakan ejen-seperti-semut untuk menemui laluan yang optimum dan alternatif. Aspek asas dalam IANRA adalah untuk mencari hala yang optimum dan sub-optimum dengan keupayaan pembiakan semut. Keupayaan ini adalah sambungan hala yang dihasilkan oleh semut induk. Generasi semut yang baru mewarisi pengenalpasti keluarga mereka, bilangan generasi dan maklumat penghalaan yang diterima oleh induk mereka semasa prosedur penghalaan. Dengan prosedur ini, IANRA berupaya menghindari kesulitan-kesulitan sedia ada dalam algoritma penghalaan AntNet, MACO dan Vektor Jarak Atas Permintaan Ad hoc (AODV).

OMNeT++ telah digunakan untuk mensimulasikan algoritma IARNA bagi WMN dan MANET. Hasil kajian menunjukkan algoritma penghalaan IANRA meningkatkan nisbah penghantaran paket data bagi kedua-dua WMNs dan MANET. Tambahan pula, ia berupaya mengurangkan kadar purata lengah hujung ke hujung dengan mengekalkan sokongan mutu perkhidmatan berbanding dengan algoritma yang lain dengan menunjukkan kecekapannya.

IANRA mengurangkan kadar purata lengah paket hujung ke hujung dengan 31.16%, 58.20% dan 48.40% dalam senario MANET 52.86%, 64.52% dan 62.86% dengan meningkatkan kadar pengeluaran paket dalam WMNs berbanding algoritma penghalaan AntHocNet, AODV dan B-AntNet dengan muatan rangkaian yang tinggi. Namun IANRA menunjukkan nisbah penghantaran paket 91.96% dan 82.77% dalam MANET, 97.31% dan 92.25% dalam WMN bagi muatan data rendah (1 paket/s) dan tinggi (20 paket/s).

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APPROVAL

I certify that a Thesis Examination Committee has met on September 11, 2009 to conduct the final examination of Ayyoub Akbari Moghanjoughi on his thesis entitled "Performance Analysis of Swarm Intelligence-Based Routing Protocol for Mobile Ad Hoc Network and Wireless Mesh Networks" in accordance with the universities and university colleges Act 1971 and the constitution of the Universiti Putra Malaysia [P.U. (A) 106] March 15, 1998. The Committee recommends that the candidate be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

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Date: 10 December, 2009

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

AYYOUB AKBARI MOGHANJOUGHI

Date: 2 December, 2009

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LIST OF ABBREVIATIONS

ACO	*Ant Colony Optimization*
AODV	*Ad-hoc On Demand Vector*
AP	*Access Point*
ARS	*Agent-based Routing Algorithm*
BA	*Backward ant*
CBR	*Constant Bit Rate*
DSDV	*Destination-sequenced Distance Vector*
DSR	*Dynamic Source Routing*
DSSS	*Direct Sequence Spread Spectrum*
FA	*Forward ant*
FHSS	*Frequency-Hopping Spread Spectrum*
FSK	*Frequency Shift Keying*
IANRA	*Intelligent AntNet based Routing Algorithm*
IN	*Intermediate nodes*
LFM	*Link Failure Message*
LTS	*Local Traffic Structure*
MAC	*Medium Access Control*
MACO	*Multicast Ant Colony Optimization based Routing*
MANET	*Mobile Ad-hoc Network*
MF	*Mobility Framework*
MIMO	*Multiple-Input and Multiple-Output*
mN	*Mobile Node*
MR	*Mesh router*
OFDM	*Octagonal Frequency-Division Multiplexing*
PSK	*Phase Shift Keying*
QAM	*Quadrature Amplitude Modulation*

QoS	*Quality of Service*
RREP	*Route Reply*
RREQ	*Route request*
RRRA	*Reactive Route Repair Ants*
S-ACO	*Simple Ant Colony Optimization*
SI	*Swarm Intelligence*
TTL	*Time To Live*
Wi-Fi	*Wireless Fidelity*
WiMAX	*Worldwide Interoperability for Microwave Access*
WMNs	*Wireless Mesh Networks*

LIST OF SYMBOLS

$\boldsymbol{\mathcal{P}}_{\mathbf{O.P}}$	Optimum path
$\boldsymbol{\mathcal{P}}_{\mathbf{N.O}}$	Non-Optimum path
$\boldsymbol{\Re}_{\boldsymbol{O.P}}$	Optimum route
$\boldsymbol{\Re}_{\boldsymbol{N.O}}$	Non-Optimum route
$\boldsymbol{l}_{\boldsymbol{l}}$	Length of longest path
$\boldsymbol{l}_{\boldsymbol{s}}$	Length of shortest path
$\boldsymbol{r}$	Length ratio
$\mathbf{P}_{\boldsymbol{i\gamma}}(\boldsymbol{t})$	probability of the ant arriving at destination
$\boldsymbol{\varphi}_{\boldsymbol{i\gamma}}(\boldsymbol{t})$	total amount of pheromone on the path from node i by γ generation of FA
$\boldsymbol{\mu}$	number of ants cross the path per second
$\boldsymbol{\rho}_{\boldsymbol{j,i}}$	probability of choosing the route when ant arrive from node ***i*** to node ***j***,
$\boldsymbol{\Delta\rho}$	Effect of ant movement at the entrance of probability table
$\aleph_{\boldsymbol{i}}^{\boldsymbol{k}}$	The neighbourhood of ant$k$ when in node i.
$\boldsymbol{F}_{\boldsymbol{d}}^{\boldsymbol{s}}$	Forward ants from source node to destination
$\mathbf{P}_{\boldsymbol{nd}}$	The probability of next hop selection by artificial ants
t	Service time per node
x	Travelling time of FAs on the selected path
$\boldsymbol{\mathcal{B}}_{\boldsymbol{jd}}^{\boldsymbol{i}}$	Boostrapped pheromone from i to d via adding cost of hopping from i to *j*
$\boldsymbol{\mathcal{V}}^{\boldsymbol{i}}$	Virtual pheromone table for node i

CHAPTER 1

INTRODUCTION

1.1 Background

Wireless and mobile communication networks have allured significant interests in recent years because of their raised flexibility and minimization of costs. Wireless networks have unique characteristics compared to wired networks. In this case nodes mobility may cause topology changes frequently. Mentioned changes in topology of wireless networks might occur between the wireless devices or mobile nodes and wired access points (Base Station). Therefore mobile network can be classified into infrastructure less (without base station) and infrastructure base (defined coverage area with access point) networks.

In order to facilitate communication within wireless networks and to provide better load management, usually routing protocols are used to discover routes and manage the network flow congestion among nodes in a network. Hence for mobile networks, design of a routing protocol is a major technical challenge due to the dynamism of the network. Currently there are many routing algorithms which are proposed to find shortest path for data transmission, but only few of them support quality of service requirements in network.

The multi-path routing protocol is to perform better load management and to provide high fault tolerance. Multiple paths are selected between source to destination and packets flow in one of these selected paths. Whenever this path is broken due to channel quality or mobility, another path in the set of existing paths can be chosen. Among multi-path based routing algorithms, Ad-hoc On Demand Vector (AODV) is popular algorithm [Mir 2006]. AODV is improvement of Destination-sequenced Distance Vector (DSDV). AODV establishes a required route only when it is needed as opposed to maintaining a complete list of routes, with DSDV. Another successful example of multi-path routing algorithms for wireless networks is known as AntNet that is a direct extension of the Simple Ant Colony Optimization (SACO) algorithm. AntNet is even closer to the real ant colonies behaviour that inspired the development of the ACO metaheuristic than the ACO algorithms for Nondeterministic Polynomial-time hard ($\mathcal{NP}$ -hard) problems. In real ants' behaviour, they initially explore the area surrounding their nest in a random manner for searching food. During the trip, the ant deposits a chemical pheromone trail on the travelling path. The concentration of pheromone deposited on paths, are increased by selection probability by ants as usual.

Here, focus is given to solve the route freezing problem in AntNet algorithm and fair bandwidth allocation to data transmission by applying several kinds of intelligent mobile agents (artificial ants) and decrease path discovery duration by ants breeding strategy. In this case simple definition of Genetic Algorithm (GA) is utilized to choice the best fitness of travelled paths information. Selected information is transferred to new generated agents through parent ants. The algorithm can be able to detect optimum path to next hop. In this research the new routing algorithm, IANRA is applied to two kind of wireless networks which are Wireless Mesh Networks (WMNs) and Mobile Ad-hoc Networks (MANET).

1.2 Problem Statement and Motivation

According to the characteristics of wireless networks, especially WMNs and MANET, the specific challenges and possible applications of these networks have raised very popular research area on wireless routing protocols. Lots of routing algorithms were proposed, among those algorithms, few were developed based on ACO (e.g. AntNet and AntHocNet).

Most of the ACO based algorithm focused to solve the routing problem and find the shortest route as an optimum path in the network. On the other hand when the optimum path ($\mathcal{P}_{O.P}$) discovered by investigator ants, the other ants follow the same path to travel to the food source or nest, according to the pheromone concentration on the travelling way. By the increase number of travellers along the discovered path, few problems occur as follows:

- Choosing the wrong path as an optimum and shortest route: As an illustration if a group of ants choose non-optimum path ($\mathcal{P}_{N.O}$) as optimum path by mistake, the other ants have more inclination to choose wrong path at the end. The concentration of pheromone increase in the mentioned path and non-optimum path becomes as an optimum route. Therefore, non-efficient network is created.

- Congestion on the optimum route: In the real world, the ants have motivation to follow the way with high pheromone concentration (the optimum route) and the selection probability of other routes decrease. Finally the selected path is usually confronted with ants' congestion. Eventually, congestion in paths is the main reason of freezing in Ant Network (AntNet) and is needed to solve by new dynamic algorithm for routing and load management.

The aforementioned challenges motivate us to study the ACO based routing algorithms and to develop a new Intelligent AntNet based Routing Algorithm (IANRA), by which the route discovery and load management in the WMNs and MANET can be improved further.

1.3 Research Aim and Objectives

The aim of this research is to provide better data traffic management in WMNs and MANET by proposing a new algorithm which is named Intelligent AntNet based Routing Algorithm (IANRA) based on the meta-heuristic swarm intelligence to solve the mentioned research problems. IANRA is able to find the global optimum path instead of all possible local optimum routes to balance the data load in the network.

To overcome the aim, the main objectives of this research are as follows:

- § To develop Intelligent AntNet based Routing Algorithm (IANRA) for data load management in the networks and to solve freezing problem in the network.
- § To evaluate the IANRA performance interms of average end-to-end packet delay, packet delivery ratio and overhead for both Wireless Mesh Networks (WMNs) and Mobile Ad-hoc Network (MANET) by realizing the optimum and sub-optimum paths.

- To investigate the IANRA behaviour under several imposed data load in networks (high, medium and low levels).
- To compare the performance of IANRA with the existing algorithms (e.g. AntNet, AntHocNet and AODV).

1.4 Thesis Scope

In this thesis IANRA algorithm is proposed to manage the load in network as well as find the optimum and near optimum shortest path from source to destination. To achieve this aim, IANRA uses several generation of ants to find optimum and sub-optimum paths. These ants are capable to breed new generation and pass all collected information to them. IANRA is proposed for both mobile Ad-hoc and wireless mesh networks. It is a multipath routing algorithm, including both reactive and proactive components for path discovery and path maintenance respectively.

For mesh networks, the routers are considered as motionless and several mobile nodes around the access point. For Ad-hoc networks, there is no fixed infrastructure for the mobile nodes. The users or mobile nodes are randomly distributed within the serving access point in WMNs or in MANET scenario. For both scenarios simulation models are designed using OMNeT++© discrete event simulator systems [OMNeT++ 2008]. For radio communication setting at the MAC layer, we rely on the OMNeT++ standard implementation of the IEEE 802.11b with 2 Mbits/s bandwidth.

1.5 Study Module

The summary of the direction taken in this research is illustrated in Figure 1.1, where the direction of thread denote to direction followed in this thesis to achieve our goals and the dotted lines represent the other directions that are already considered in previous researches.

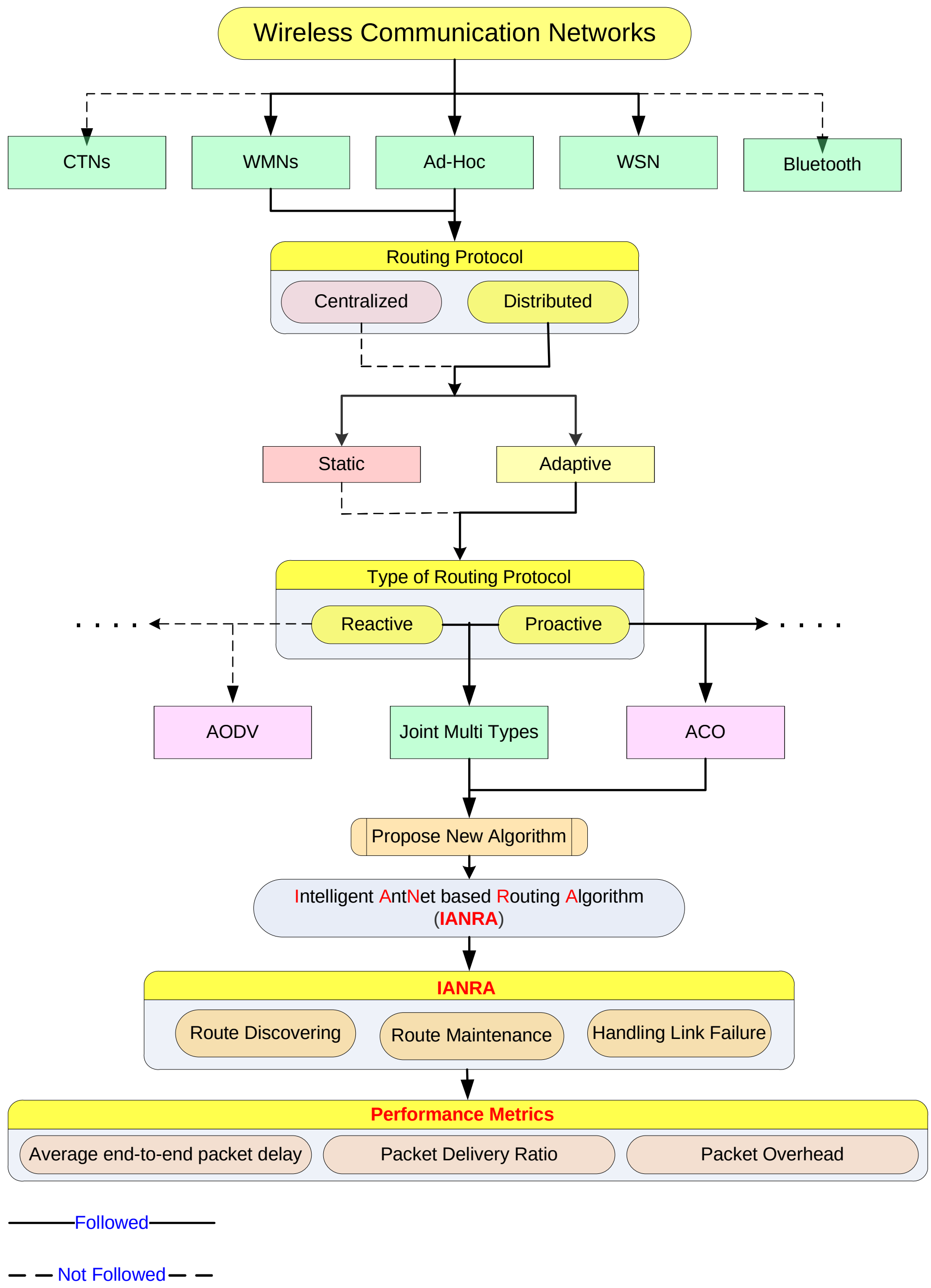

Figure 1.1. Study Module

1.6 Thesis Organization

The thesis is organized in terms of six Chapters. Chapter 2 discusses literature review and analysis of common routing protocols in WMNs and MANET. At the beginning of second chapter, the infrastructures and characteristics of WMNs and MANET have been discussed in details.

In Chapter 3, the Swarm Intelligence (SI) based routing algorithms are introduced along with some recent proposed SI algorithms for wireless networks. The related heuristic and metaheuristic example to find the near optimum solution for exciting algorithms is presented in details too.

In Chapter 4, the proposed IANRA routing algorithm has been presented and analyzed for both WMNs and MANET networks for load management purpose. For mentioned two networks two different models are considered. In this chapter the IANRA is described in four phases; (i) Path discovery, (ii) Route maintenance and (iii) Link failure solution.

The results and discussions of the IANRA are presented in Chapter 5, followed by conclusion in Chapter 6.

CHAPTER 2

REVIEW AND ANALYSIS OF ROUTING ALGORITHMS IN WIRELESS COMMUNICATION NETWORKS

2.1 Overview

The appearance of wireless communications dates from the late 1800s, when M. G. Marconi did the pioneer work establishing the first successful radio link between a land-base station and tugboat. Since then, wireless communication systems have been developing and evolving with a furious pace. The main target of wireless communication networks is to provide information services, e.g., voice and data to mobile users via related wireless interfaces. On the other hand wireless networks provide unprecedented freedom and mobility for a growing number of laptop, PDA and other wireless device users who no longer need wires to stay connected with their workplace and the Internet.

By increasing interest of using the available wireless services, several architectures have been created. As an illustration, Wireless Local Area Network (WLAN), Mobile Ad-hoc Network (MANET), Wireless Mesh Networks (WMNs) and Wireless Sensor Networks (WSN) are current architectures. For each of mentioned networks the provider must produce the acceptable bandwidth and hardware to support network targets based on applications and type of using data (e.g., voice and video). Besides, networks should support all possible network protocols for user's requirements. One of the most important protocol in communication data networks, without considering wire based or wireless networks, is network routing protocol.

Current wireless networks especially WMNs will be tightly integrated with the Internet, and IP has been accepted as a network layer protocols for many wireless networks including WMNs. However, routing protocol for WMNs are different from those in wired and cellular networks [Akyildiz 2005a]. On the other hand, WMNs share common features with ad-hoc networks, the routing algorithms which developed for ad-hoc networks can be applied to WMNs. Besides, sharing the network resources among many network users is one of the main objectives of mobile ad-hoc and wireless mesh networks. Therefore this study is focused on routing protocol in coming section.

In this chapter, wireless mesh networks and mobile ad-hoc network are introduced and discussed in details. Afterwards available and most popular routing algorithms for wireless data networks, which are applicable for WMNs and MANET, are considered with related objectives, advantages and disadvantages.

2.2 Wireless Communication Networks

Wireless communication is one of the fastest-growing technologies and mobile wireless networking has enjoyed a dramatic increase in popularity the last few years, although the technology has existed for more than twenty years and has been commercially available for more than ten years [Chuah 2006]. In current communications world, wireless networks can be found on college campuses, international airports, in office buildings, and in many public areas.

Infrastructure of wireless networks has been created in several levels based on variety of applications. As a general illustration Figure 2.1 shows wireless communication systems at all levels [Mir 2006].

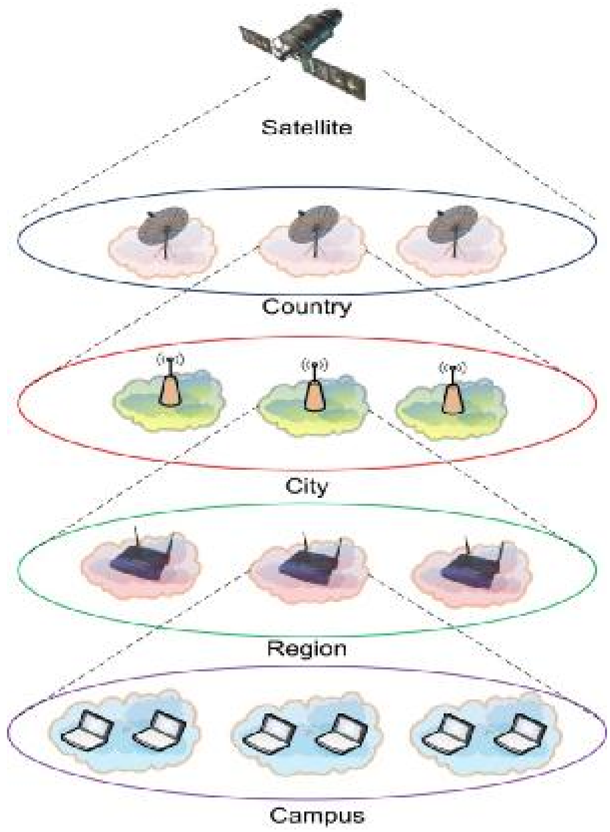

Figure 2.1. Wireless Communication Systems, from Satellite to WLAN

Each wireless user has a wireless network interface (Network Adapter) for communication over the wireless medium. This interface (NIC[1]) is responsible for authentication, confidentiality, and data delivery. In a common wireless LAN, the Access Point (AP) recognizes the wireless user through a unique ID called the

[1] Network Interface Card

Service-Set Identification (SSID). SSID is like a password-protection system that enables any wireless client to join the wireless network.

IEEE has defined the specifications for wireless LAN. This standard for wireless LANs includes 802.11 and its family: 802.11a, 802.11b, 802.11g and draft 802.11n. The Table 2.1 shows some details about this standard and category of its family [Mir 2006, IEEE 2008].

Table 2.1. IEEE 802.11and family standards

IEEE	*Release Date*	*Technique*	*Band GHz*	*Modulation*	*Rate (Mbps)*	*Range Indoor*	*Range Out*
802.11	Sep’97	FHSS	2.4	FSK	1 & 2	~30m	~100m
		DSSS	2.4	PSK	1 & 2		
802.11a	Oct’99	OFDM	5.725	PSK or QAM	6 to 54	~35m	~120m
802.11b	Oct’99	DSSS	2.4	PSK	5.5 & 11	~38m	~140m
802.11g	June’03	OFDM	2.4	Different	22 & 54	~38m	~140m
802.11n	Oct’08*	MIMO	2.4 and/or 5	MSM**	108	~70m	~250m

* Information for 802.11n is based on Draft 2

** New Multi-Streaming Modulation

Wireless networks are classified according to the scale and topology. For example the coverage area for cellular wireless networks is wider than Wi-Fi network. Alternatively, topology of interconnection and applied protocols for each of them is completely different.

Mobile ad-hoc and wireless mesh networks are two existing popular category of wireless networks. Therefore, this research is focused on mentioned networks.

Proposed routing algorithm (IANRA) for load management purpose is evaluated and applied on mentioned networks. Following sections (2.2.1 and 2.2.2) give some details about WMNs and MANET.

2.2.1 Wireless Mesh Networks (WMNs)

WMNs consist of static wireless routers, some of which, called gateways and wireless mesh clients. Gateways are directly connected to the wired infrastructure (backbone). Wireless user stations are able to connect to the backbone via wireless routers in WMNs topology. The integration of wireless mesh networks with other networks such as the Internet, cellular, IEEE 802.11, IEEE 802.15, 802.16, sensor networks, etc., can be accomplished through the gateway and bridging functions in the mesh routers [Akyildiz 2005a, Bejerano 2007].

2.2.1.1 Network Architecture

WMNs consist of two types of nodes: wireless mesh clients and mesh routers. The wireless routers are interconnected with each other via wireless links and provide communication services to mobile or static users in their vicinities. Some of the routers are directly connected to a fixed infrastructure (i.e., like the wired base Internet) and serve as gateways for other wireless routers [Bejerano 2007]. Mesh routers can achieve the same coverage, in compared with conventional wireless routers, with much lower transmission power through multi-hop communications. Optionally, the Medium Access Control (MAC) protocol in a mesh router is enhanced with better scalability in a multi-hop mesh environment [Akyildiz 2005a].

Mesh and conventional wireless routers are usually built based on similar hardware platform. Mesh routers can be built based on dedicated computer systems (e.g. embedded systems) and look compact, as shown in Figure 2.2 [Solution 2008a, Solution 2008b].

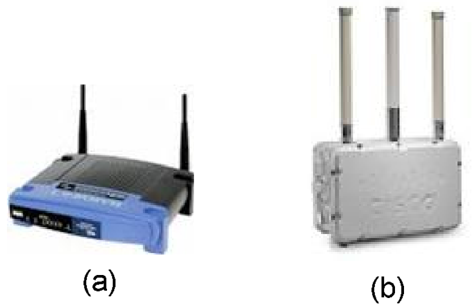

Figure 2.2. Examples of Mesh Routers Based on Different Embedded Systems: (a) Indoor and (b) Outdoor Solutions

The mesh clients usually have one wireless interface to connect to mesh router in its coverage area. As a consequence, the software and hardware platform for mesh clients can be much easier than those for mesh routers. Mesh clients have a higher variety of devices compared to mesh routers. Mesh clients in WMNs can be as a PC, laptop, PDA, IP phone, wireless RFID reader, BACnet[2] controller and many other devices. Some of mesh clients are shown in Figure 2.3.

Figure 2.3. Examples of WMNs Clients

[2] Building Automation and Control networks (BACnet)

The architecture of WMNs can be classified into three main groups based on the functionality of the nodes [Akyildiz 2005a]:

- Infrastructure/Backbone WMNs.
- Client WMNs
- Hybrid WMNs.

The first one, WMN infrastructure/backbone can be built using various types of radio technologies, in addition to the mostly used IEEE 802.11 technologies. With gateway functionality, mesh routers can be connected to the Internet. One of the advantages of WMNs is ability of conventional clients with Ethernet interface to connect to mesh routers via Ethernet links. The architecture of infrastructure/backbone WMNs is shown in Figure 2.4, where dash and solid lines denote wireless and wired links, respectively. This type of wireless mesh networks includes mesh routers [Mir 2006, Akyildiz 2005a].

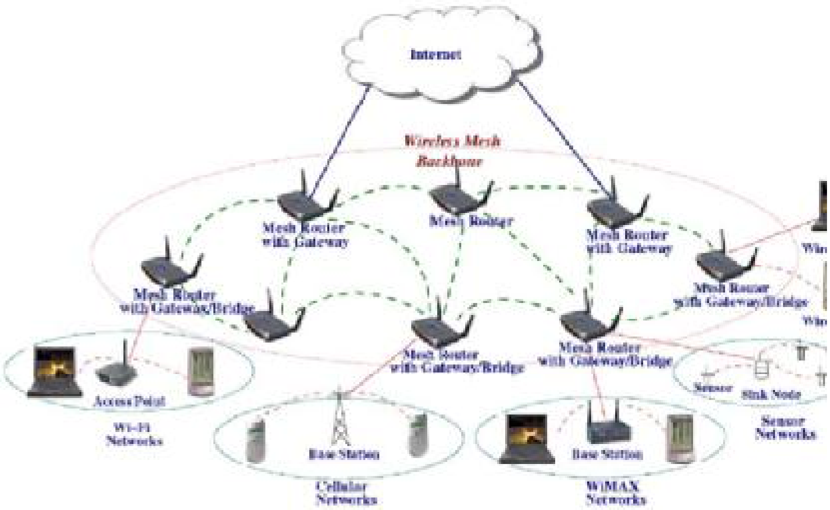

Figure 2.4. Infrastructure/Backbone WMNs

The second architecture of WMNs is client WMNs. Client meshing provides peer-to-peer networks among client devices. In this type of architecture, client nodes constitute the actual network to perform routing and configuration functionalities as well as providing end-user application to customers. Therefore, a mesh router is not required for these types of networks. Client WMNs are usually formed using one type of radios on devices. In client WMNs, a packet destined to a node in the network hops through multiple nodes to reach the destination [Mir 2006, Akyildiz 2005b]. The simple and basic architecture is shown in Figure 2.5.

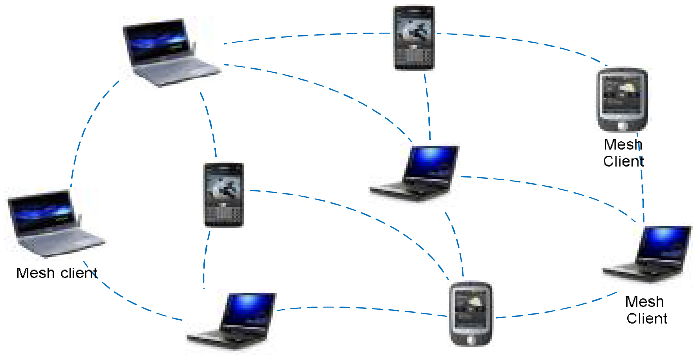

Figure 2.5. Clients of WMNs

The Hybrid WMNs is a complete architecture of wireless mesh networks. Since this architecture is the combination of infrastructure and client meshing, as shown in Figure 2.6. Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. While the networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks; the routing capabilities of clients provide improved connectivity and coverage inside the WMNs [Akyildiz 2005b]. As mentioned before, hybrid WMNs commonly adopts the IEEE 802.11 standard at the Physical and MAC layers [Mir 2006, Pirzada 2007]. The hybrid architecture will be the most applicable case in our opinion.

Figure 2.6. Hybrid Wireless Mesh Networks.

2.2.1.2 Characteristics

The main characteristics of WMNs involve the following features:

The first characteristic of WMNs is multi-hop wireless network. The objective to develop WMNs is to extend the coverage range of current wireless networks without sacrificing the channel capacity. The other objective is to provide Non-Line-Of-Sight (NLOS) connectivity among the clients and users without direct Line-Of-Sight (LOS) links [Krishnamurthy 2002]. For these requirements, the mesh-style multi-hoping is essential. Therefore, WMNs is able to support multi-hop wireless network.

Compatibility and interoperability with existing wireless networks are other features of WMNs. As an illustration, WMNs is created based on IEEE 802.11 technologies [Inc 2005, Walker 2005], thus must be made compatible with IEEE 802.11 standards in the sense of supporting both mesh capable and conventional Wi-Fi clients. So

WMNs also need to inter operable with other wireless networks such as WiMAX, ZigBee [Alliance 2005], and cellular networks [Akyildiz 2005a].

Multiple type of network access is another feature for WMNs. Both backhaul access to the Internet and peer-to-peer (P2P) communications are supported in WMNs [Jangeun 2003]. Wireless mesh network support for ad-hoc networking and capability of self-forming, self-healing, and self-organization [Akyildiz 2005b, Tierney 2007].

In WMNs, mobility is depending on the type of mesh nodes. Mesh routers usually have minimal mobility, while mesh clients can be motionless or mobile nodes. On the other hand, mesh routers usually do not have strict constraints on power consumption. However, mesh clients may require power efficient protocols. For example, a mesh-capable sensor requires its communication protocol to be power efficient [Akyildiz 2005a, Akyildiz 2005b].

2.2.2 Mobile Ad-hoc Networks (MANET)

A simple structure of ad-hoc networks is by definition, created on demand, without any specific infrastructure. They are often considered as an extension of the range of Internet access points, providing multi-hop wireless access to them [Michalak 2005]. Besides, Mobile Ad-hoc Networks (MANET) have had a profound impact in the world of computer networks. Characterized by any time and any where untethered establishment of a wireless network, the MANET infrastructure enables location-independent services. MANET consists of a loosely connected domain of routers. Therefore, ad-hoc networks do not need any fixed infrastructure to operate and support dynamic topology scenarios in which no wired infrastructure exist [Mir 2006, Michalak 2005, Chakeres 2007]. Figure 2.7 shows a sample of mobile ad-hoc networks applications in military networks [Dillingham. 2007].

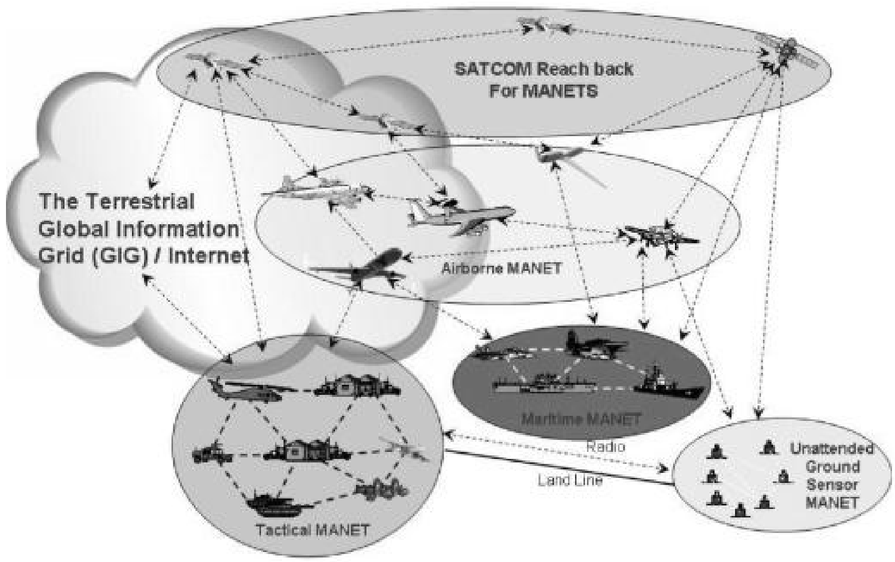

Figure 2.7. A Sample of MANET Applications in Military Networks

2.2.2.1 Architecture of MANET

A mobile ad-hoc network is a collection of mobile devices equipped with a transmitter and receiver, connected in the absence of fixed infrastructure. Each of the wireless nodes is able to make connection with available wireless mobile or motionless neighbour nodes in its coverage area. MANET offers multi-hop communication, in effect network nodes communicating via other nodes. Nodes rely on each other to establish communication, thus each node acts as a router. Therefore, in a mobile ad-hoc network, a packet can travel from a source to a destination either directly, or through some set of intermediate packet forwarding nodes [Bakht 2004].

2.2.2.2 Characteristics

Mobile ad-hoc network is defined with characteristics such as purpose-specific, autonomous and dynamic. In comparison with fixed wireless networks, there is no master slave relationship that exists in a mobile ad-hoc network [Bakht 2004]. One of the unique features for this network is automatic discovery of available services. Each time a new service becomes available, an ad-hoc networking device has to configure the usage of the new service. In general target of MANET, wireless nodes should be able to enter or leave the network as they wish. Thus, every node acts as both a host and router, and the network must be intelligent enough to handle network dynamically. This characteristic is called self-stabilization [Mir 2006, Bakht 2004].

Security of this network is a key issue. Ad-hoc networks are vulnerable to attacks. An intruder can easily attack ad-hoc networks by loading available network resources and distributing the normal operation of routing protocols by modifying packets [Mir 2006]. MANET has several types of applications. Some of mobile ad-hoc network applications are as follows:

- Emergency rescue operations
- Military (battle zone)
- Home/Office networks
- Conferencing and etc.

2.3 Routing in Wireless Networks

One of the most important functions in computer networking, especially in wide area networks, is routing protocol for packet transmission. In wireless networks (e.g., mobile ad-hoc networks), the lack of a backbone infrastructure makes packet routing a challenging task. In view of the fact that a routing protocols should be able to automatically recover from any problem in a finite amount of time without human intervention [Mir 2006].

Conventional routing protocols are designed for non-moving infrastructure and assume that routes are bidirectional, which is never the case for MANET and WMNs networks. Identification of related mobile clients, routers, etc, and correct routing of data packets while the node is moving are certainly challenging since existing routing protocols are focused on mobile network infrastructures and supporting QoS with dynamic techniques [Mir 2006, Forouzan 2007].

Routing algorithms can be classified in several ways. One of the routing classifications is based on routing decision for data packets. By this taxonomy, the routing algorithms are able to divide into two groups; (i) centralized and (ii) distributed routing. In centralized routing, only selected and designated node can make a decision, such as selecting optimum paths for data transmission. The distributed routing protocols behaviour is completely different than centralized one. In distributed routing protocols, all nodes contribute in making the routing decision for each packet. In other words, a distributed routing algorithm allows a node to get information about routing from all the nodes, but the least-cost path is determined locally [Mir 2006, Forouzan 2007, Tanenbaum 1996].

Routing algorithms can also be classified as either static or dynamic[3]. In static routing, a network establishes an initial topology of paths. All initial paths addresses must be loaded onto routing tables, which are called static routing table, at each node for a certain period of time. By considering static routing protocol, the size of the network should be small enough to make it controllable. Also, if a failure occurs in the network, it is not able to respond immediately. The mentioned problems will be solved by using dynamic routing. In dynamic routing, the state of the network is learned through the communication of each router with its neighbours. Each router can find the best path to a destination by receiving updated information from nearby nodes [Mir 2006, Forouzan 2007].

Dynamic routing protocols are divided into two category based on path discovery behaviour. These two categories consist of "Reactive" and "Proactive (table-driven)" routing protocols. The reactive protocols find a route on demand by flooding the network with Route Request (RREQ) packets (e.g., AODV, MAODV, RAODV and etc.). The main disadvantages of such algorithms are "High latency time in route finding" and "Excessive flooding can lead to network clogging". On the other hand, proactive protocols maintain updated lists of destinations and their routes by periodically distributing routing tables throughout the network (e.g., AntNet, DSDV and etc.). The main disadvantages of such algorithms are "Respective amount of data for maintenance" and "Slow reaction on restructuring and failures" [Mir 2006, Pirzada 2007, Forouzan 2007]. It seems that, the join type of reactive and proactive protocols will improve routing performance in discovery phases.

[3] Some of the references called "adaptive routing algorithms" instead of dynamic routing algorithms.

Routing algorithms can be differentiated by several key characteristics which are as follows [Mir 2006]:

- *Accuracy*. A routing algorithm must operate correctly to find and decide the destination path in reasonable time.
- *Simplicity*. Low complexity of routing algorithm is very important where routers with limited physical resources involve software [Cormen 2003].
- *Optimality*. This characteristic refers to the ability of algorithm to choose the best route.
- *Stability*. Routing algorithm must perform correctly in the fact of unforeseen circumstances, such as node failure, corruptions of routing table and etc.
- *Adaptability*. The algorithm should be able to adapt load increases or decreases, when failure happens in a network.
- *Convergence*. Routing algorithms must converge rapidly when a network distributes routing update messages.
- *Load balancing*. A good routing algorithm balances over illegible links to avoid having a heavily and temporarily congested link. The following section gives more details on load balancing which is the main target of the proposed algorithm (IANRA) in this thesis.

2.4 Existing Routing Protocols for MANET and WMNs

Wireless mesh networks will be integrated with the Internet, and IP has been accepted as a network layer protocol for many wireless networks including WMNs. Although routing protocols for WMNs and MANET are different from those in wired and cellular networks. Since WMNs share common features with MANET, the routing protocols develop for ad-hoc networks can be applied to WMNs [Akyildiz 2005a, Akyildiz 2005b].

In this research reviewing the routing protocols is divided in two parts; (i) non-swarm intelligence base routing protocols and (ii) the routing protocols based on Swarm Intelligence (SI). The first part of current routing protocols is subject of this section and the second one will be describe in chapter three as well. Figure 2.8 shows the classification of multi-hop routing protocols for wireless networks with supporting mobility for nodes.

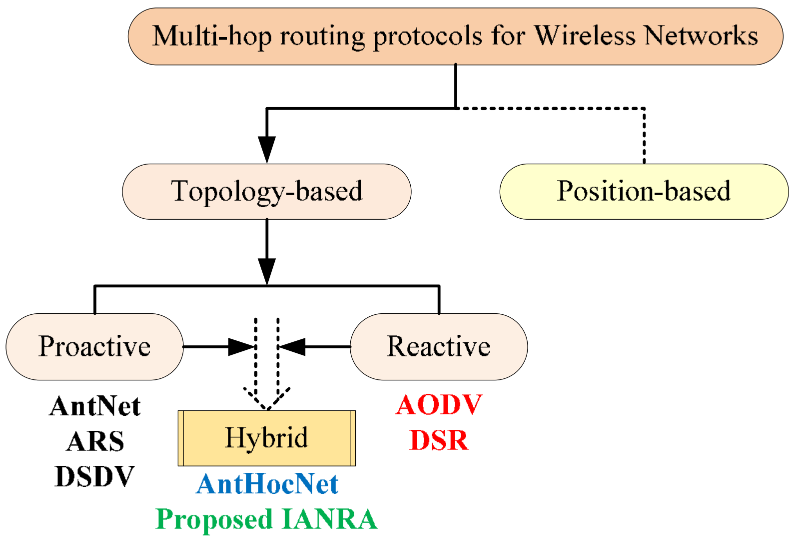

Figure 2.8. Classification of Wireless Networks Routing Protocols

The main objective of using multi-path routing in multi-hop wireless networks is to perform the better load management and to provide high fault tolerance [Akyildiz 2005a, Mueller 2004]. Multiple paths are selected between source and destination. Packets flow in one of these selected paths. When link is broken on a path due to a bad channel quality, network interface corruption or mobility, another path in the set of existing paths can be chosen. Therefore, without waiting for setting up a new routing path, the end-to-end delay and fault tolerance can be improved.

2.4.1 Destination-Sequenced Distance Vector (DSDV)

The DSDV protocol is a table-driven routing protocol based on the improved version of classical Bellman-Ford routing algorithm. In the DSDV routing protocol, a node holds a routing table containing all possible destinations within the network and the number of hop to each destination. On the other hand, DSDV is based on distance-vector routing and thus bidirectional links [Mir 2006, Perkins 2006].

The structure of routing table for this protocol is very simple. Each table has sequence number that is incremented every time a node sends an update message. Routing tables are periodically updated when the topology of the network changes. The packet overhead of the DSDV protocol increases the total number of nodes in ad-hoc network. This fact makes DSDV suitable for small networks [Boukerche 2000].

A limitation of DSDV is that it provides only on route for source /destination pair. On the other hand, in large ad-hoc networks, the mobility rate and therefore the overhead increase, making the network unstable to the point that updated the packets might not reach nodes on time [Mir 2006]. Some of the other limitations for DSDV are given briefly as follow:

- Wastage of bandwidth due to unnecessary advertising of routing information even if there is no change in the network topology [Patel 2000].

- DSDV doesn't support multi-path routing.
- It is difficult to determine a time delay for the advertisement of routes [Gorantala 2006].
- It is difficult to maintain the routing table's advertisement for larger network. Each and every host in the network should maintain a routing table for advertising. But for larger network this would lead to overhead, which consumes more bandwidth [Perkins 2006].

With considering mentioned limitation of DSDV routing protocol and its family such as A-DSDV[4], R-DSDV[5] and etc, it seems that these protocols are not suitable for WMNs and MANET, because the aforesaid protocols are not designed for multi-path networks.

2.4.2 Dynamic Source Routing (DSR)

The Dynamic Source Routing (DSR) protocol is an on-demand, or in other words, source-initiated routing protocol in which a source node finds an unexpired route to a destination to forward the packet. DSR quickly adapts to topological changes and is typically used for networks in which mobile nodes move with moderate speed. One of the most important advantage of DSR in comparison to DSDV and its family is reducing the overhead [Mir 2006, Kadri 2008]. Overhead is significantly reduced with this protocol, since nodes do not exchange routing table information when there are no changes in the network topology (RFC 4728) [Johnson 2007].

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[4] Adaptive Destination-Sequence Distance Vector
[5] Randomized version of Destination-Sequence Distance Vector

DSR creates multiple paths from a source to a destination, eliminating route discovery when the topology changes. Similar to the most mobile ad-hoc networks, DSR has two phases: (i) path (route) discovery phase and (ii) route maintenance [Johnson 2007]. In first phase, route discovery is initiated when a node wants to send packets to another node and no unexpired route to the destination is in its route cache[6], therefore DSR route cache entries do not have lifetimes [Lu 2003]. Lake of lifetime for route discovery phase is one of disadvantages of dynamic source routing protocol. This problem has been solved with another on-demand routing protocol which is called "Ad-hoc On-demand distance vector (AODV)".

Besides of advantages of DSR, it has some disadvantages in comparison with other same on-demand routing protocols (e.g., AODV). As an illustration, DSR performs best in low mobility or less stressful situations (lower traffic load) because cached routes helpful in low mobility, but less helpful in high mobility cause of pollution and congestion on route cache [Lu 2003].

2.4.3 Ad-hoc On-demand Distance Vector (AODV)

The Ad-hoc On-demand Distance Vector (AODV) routing protocol is a very simple, efficient, and effective routing protocol for mobile ad-hoc networks and mobile part of wireless mesh networks which do not have fixed topology. This routing protocol is an improvement over DSDV and is source-initiated routing scheme capable of both unicast and multicast routing. Besides, AODV was motivated by the limited bandwidth that is available in the media, it is used for wireless communications. It

[6] Route cache is similar to routing table in Table-driven routing protocols (e.g., AODV). DSR Route cache has more information about routing and routing table in AODV is able to limit these data.

borrows most of the advantageous concepts from DSR and DSDV algorithms. The on demand route discovery and route maintenance from DSR and hop-by-hop routing, usage of node sequence numbers from DSDV make the algorithm cope up with topology and routing information [Gorantala 2006, Sarkar 2008]. AODV offers quick convergence when a network topology changes because of any node movement or link breakage. In such cases, AODV informs all nodes so that they can invalidate the routes using the lost node or link. This protocol adapts quickly to dynamic link conditions and offers low processing, memory overhead, and network utilization [Forouzan 2007, Sarkar 2008].

Loop-free AODV is self-starting and handles large numbers of mobile nodes. It allows mobile nodes to responds to link breakages and changes in network topology in a timely manner. The algorithm primary features are as follows [Mir 2006, Sarkar 2008]:

- It broadcasts packets only when required.
- It distinguishes between local connectivity management and general maintenance.
- It disseminates information about changes in local connectivity to neighbouring mobile nodes that need this information.
- Nodes that are not part of active paths neither maintain any routing information nor participate in any periodic routing table exchange.
- A node does not have to find and maintain a route to another node until the two nodes communicate.

With considering mentioned advantages and disadvantages, AODV shows better performance rather than DSDV and DSR routing protocols. On the other hand, AODV has covered complete advantages of DSDV and DSR approximately. Also, ad-hoc on-demand distance vector is applicable to WMNS and especially MANET. Therefore AODV routing protocol is the best candidate to be compared and evaluate with proposed swarm intelligent based IANRA routing algorithm.

2.5 AntNet Based Routing Algorithms

Swarm Intelligence (SI) is a computational intelligence technique involving the study of collective behaviour in decentralized routing protocols. Also Swarm Intelligence can merge reactive and proactive routing algorithm but the others like AODV, DSR and SAODV, only can design base of one of the proactive or reactive routing protocol. By applying swarm intelligence for routing protocol the pheromone table uses instead of routing table. Due to pheromone evaporation in the pheromone table the probability of path selection for one certain path is changing dynamically. Therefore it makes intelligence decision by path researcher ants. Since the aim of proposed routing algorithm is to find shortest paths and at the same time it should try to solve route freezing problem, Swarm Intelligence method seems better than others and it was the main motive of designing the proposed algorithm based on SI and investigate its behaviour.

This section gives some details about ACO based algorithms especially for routing. In the first part in section 3.2.3.1, simple ant colony optimization for finding the shortest path is presented as well as the main idea behind AntNet algorithm. Afterward, Agent-based Routing Algorithm (ARS) is discussed followed by simple

AntNet. ARS had proposed to add some QoS requirements on the S-AntNet and enhance the basic idea of ant colony optimization. Last section of current chapter is introduced AntHocNet, which is based on very strong aims. AntHocNet is proposed by the research group in Institute for Artificial Intelligence in Manno-Switzerland. Currently, aforementioned research group kept AntHocNet project alive and they have created the test-bed of this project. In the urban scenario for AntHocNet test-bed Lugano in Switzerland considered as reference city [DiCaro 2008, DiCaro 2006]. The Figure 3.4 [DiCaro 2006] shows the street structure in the urban scenario by Gianni A. Di Caro and et al.

2.5.1 S-AntNet

The firs experiment with ant colonies optimization had started with Simple ACO or S-ACO for short. S-ACO had used simple kind of ants as mobile agents for path searching with real ants' behaviour. Hence, it is named S-AntNet instead of S-ACO for this algorithm. The applied ants for S-AntNet can be thought of as having two working modes: forward and backward. The authors of S-AntNet have considered a variable τ_{ij} called artificial pheromone trail to each arc (i, j) of graph $G = (N, A)$. As mentioned before in pervious section pheromone trails were read and written by the mobile ants. They also considered pheromone evaporation in this experiment. In the real ant colonies, pheromone intensity decreases over time because of evaporation. In S-AntNet evaporation is simulated by applying an appropriately defined pheromone evaporation rule.

Each ant in S-AntNet builds, starting from the source node. At each node, local information stored on the node itself or on its outgoing arcs is sensed by the ant and used in stochastic way to decide which node to move to next. At the beginning of discover processing, a constant amount of pheromone (e.g., $\tau_{ij} = 1, \ \forall(i,j) \in A$) is assigned to all the arcs. When located at a node i an ant k uses the pheromone trails τ_{ij} to compute the probability of choosing j as next node [Dorigo 2004a, Dorigo 2004b]:

$$\rho_{ij}^{k} = \begin{cases} \dfrac{\tau_{ij}^{\alpha}}{\sum_{l \in \aleph_i^k} \tau_{il}^{\alpha}}, & if\ j \in \aleph_i^k \\ 0, & if\ j \notin \aleph_i^k \end{cases} \tag{2.1}$$

Where $\aleph_i^k$ is the neighbourhood of ant k when in node i. In S-AntNet the neighbourhood of a node i contains all the nodes directly connected to node i in the graph $G = (N, A)$, except for the predecessor of node i. Only in case $\aleph_i^k$ is empty, which corresponds to a dead end in the foresaid graph, node i's predecessor is included into $\aleph_i^k$.

The main weakness point of S-AntNet is probability of occurring loop by researcher ants. As an illustration, researcher ants may return to the visited node by themselves after crossing several hops.

2.5.2 Agent-based Routing System (ARS)

The Agent-based Routing System (ARS) is based on Ant Colony Optimization and is a framework for building ant-inspired algorithms. ARS was evaluated through simulation packet-switched point-to-point network. To investigate whether it is able to increase the throughput or not while avoiding package loss in a heavily loaded network, when packages are sent between two individual routers [Oida 2000, Oida 1999].

Sets of pre-discovered feasible paths, for all possible destination nodes, are cached on each node. Several classes of bandwidth requirements are supported by ASR. Each class has at least a certain amount of unreserved bandwidth unite (bottleneck bandwidth). A different set of feasible paths is unique for a given destination node and a bandwidth class. ARS is based on AntNet where ants are used to build probabilistic routing tables for datagram routing only. For each bottleneck bandwidth class, there exists a different colony of ants. All FA agents of a colony only use links whose unreserved resources are not less than a bottleneck bandwidth assigned to that colony. Feasible paths are discovered by ants of different colonies concurrently to build probabilistic tables for routing datagram's. Individual probes (one at a time) are launched to follow a rediscovered feasible path of a certain bandwidth class towards an egress node. Resources are reserved along the way of the probe. Probes are not routed via probabilistic routing tables but are guided via fixed cached paths favouring the shortest one. Possible criticisms for this approach are that pre-discovered paths could easily be out of-date and a shortest path is not necessarily an optimal one. The communication overhead is the sum of the bandwidth allocated for operation of all agents including the probes [Tadrus 2003].

ASR presents an easy implementation way when the bottleneck bandwidth is m. Let $r(s,n)$ be the number of unreserved resources of link (s,n) which is a link between nodes s and n also N_s denote the set of neighbouring nodes of node s. In every node s in a network, when node $n \in N_s$ satisfies $r(s,n) < m$, node n is removed from set N_s (as if link (s,n) had failed), and then all routing probabilities in node s are normalized as follow:

$$\left(\rho_{d,n'}^{s,m}\right)' = \frac{\rho_{d,n'}^{s,m}}{\left(\sum_{i \in N_s} \rho_{d,i}^{s,m}\right)} \;, \quad \forall n' \in N_s \; and \; \forall d \in S = \{s\} \qquad (2.2)$$

After that, when node n satisfies $r(s,n) \geq m$, node n is added to set N_s (as if link (s,n) had recovered), and then all routing probabilities in node s are normalized again by Equation 3.8. ASR also presents functions for supporting QoS requirements and for efficiently allocating network-wide resources according to user requests. The extended AntNet proposed by K. Oida et al, is the first bandwidth and hop-count constrained routing algorithm based on mobile agents [Oida 2000, Oida 1999]. The efficiency of mentioned algorithm was based on resource management, in which mobile agents gather current link states on their way for examining the availability of feasible paths maintained in each node [Oida 2000]. Finally, ASR was evaluated in three aspects: efficiency, scalability, and extensibility.

2.5.3 AntHocNet

One of current routing algorithm based on AntNet for mobile ad-hoc network is AntHocNet [DiCaro 2006, Ducatelle 2006, Caro 2004]. It is a hybrid multipath algorithm based on the principle of ACO routing and also based on the integration of a reactive and a proactive approach to setup, maintain, and improve paths. Two features of this algorithm are Reactive and Proactive. It does not maintain routes to all possible destinations at all times (like the original ACO algorithms for wired networks), but only sets up paths when they are needed at the start of a data session [DiCaro 2005]. AntHocNet combines the typical path sampling behaviour of ACO algorithms with a pheromone bootstrapping mechanism derived from Bellman-Ford algorithms to adaptively update pheromone tables which playing the vital role of routing tables [Caro 2004, DiCaro 2005].

In reactive phase ant agents called reactive forward ants are launched by the source in order to find multiple paths to the destination, and backward ants return to the source to set up the paths [Ducatelle 2004, Ducatelle 2006, F. Ducatelle 2005]. Based on the common practice in ACO algorithms, the paths are set up in the form of pheromone tables indicating their respective quality. After the route setup, data packets are routed over the different paths following these pheromone tables stochastically. While the data session is going on, the paths are monitored, maintained and improved proactively using different agents, called proactive forward ants. The algorithm reacts to link failures with either a local route repair or by warning the preceding nodes on the paths [DiCaro 2005, DiCaro 2006, F. Ducatelle 2005].

Figure 2.9. The Map of Lugano City in Switzerland That Has Been Used to Define the Cityscape in Urban Scenario of AntHocNet.

The summary of AntHocNet shows that, when a source node s starts a communication session with a destination node d, and it does not have routing information for d, it broadcasts a reactive forward ant F_d^s. Due to this initial broadcasting, each neighbour of S receives a replica $F_d^s(k)$ of F_d^s. The task of each ant $F_d^s(k)$ is to find a path connecting s and d. The routing information of a node i is represented in its pheromone table going from i over neighbour n to reach destination d. The ant will choose its next hop n with the probability table, τ^i while crossing i towards neighbour n. Equation 3.9 shows, P_{nd} the probability of next hop selection by artificial ants. Where N_d^i is the set of neighbours of i node and β_1 is a parameter value which can lower the exploratory behaviour of the ants [DiCaro 2005].

$$P_{nd} = \frac{\left(\left(\tau_{nd}^{i}\right)^{\beta_2}\right)}{\left(\sum_{j \in N_d^i} \left(\tau_{jd}^{i}\right)^{\beta_2}\right)}, \qquad \beta_2 \geq \beta_1 \tag{2.3}$$

In AntHocNet experiments, β_2 was set to 20. Setting the routing exponent so high means that if several paths have similar quality, data packets spread over them. However, if one of selection paths is clearly better than another, it will almost always be preferred [Ducatelle 2004, DiCaro 2005]. Figures 2.10 and 2.11 shows simulation environment of AntHocNet in an urban and open space scenario.

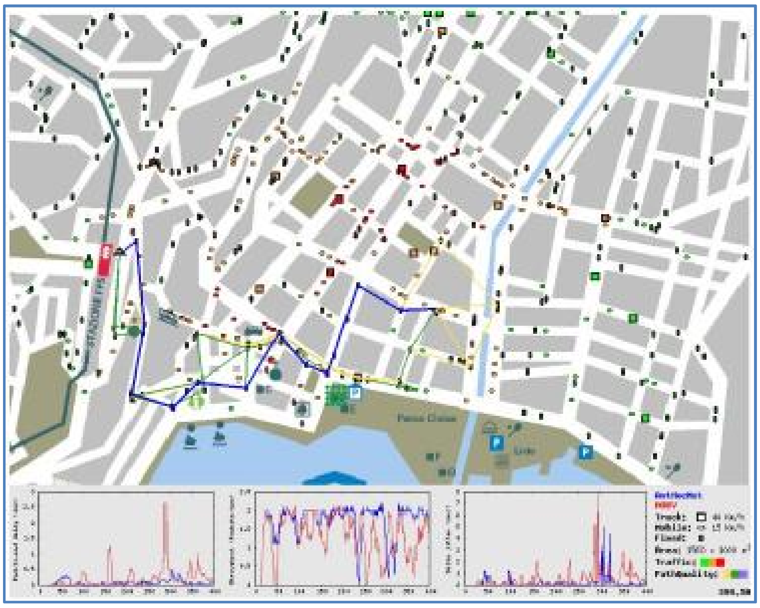


Figure 2.10. Simulation Environment of AntHocNet in an Urban Scenario

The probabilistic routing strategy leads to data load spreading according to the estimated quality of the available paths on the network. If the estimates are kept up to date, it leads to load managment on the network automatically. By adapting the data traffic, the nodes try to spread the data load evenly over the networks.

As a result of AntHocNet project, it issues that AntHocNet has a performance advantage over AODV. The advantages are in terms of packet delivery ratio, average end-to-end delay, average jitter, and scalable for larger, sparser and dynamic environments. On the other hand, AntHocNet shows better results in comparison to foregoing AntNet based routing algorithms. However, AntHocNet is less efficient in terms of routing overhead.

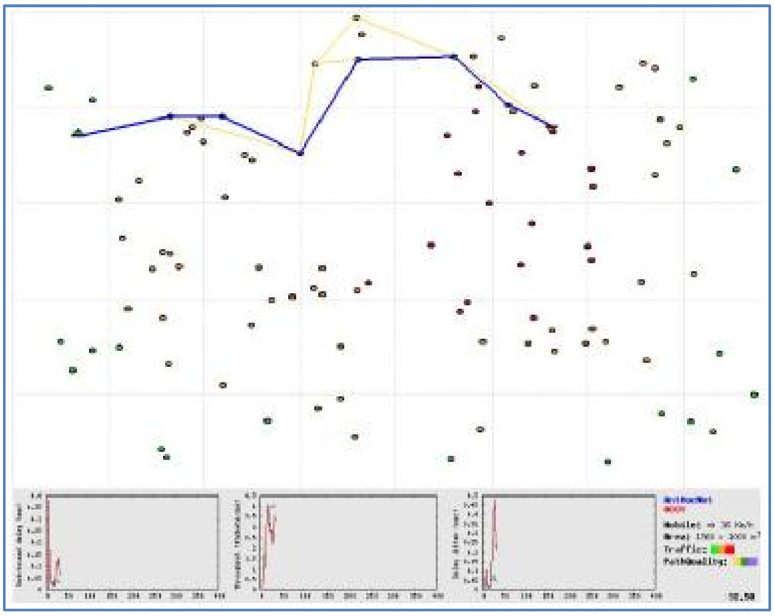


Figure 2.11. Simulation Environment of AntHocNet in an Open Scenario

In this research, AntHocNet has selected as one of references algorithms in swarm intelligence based algorithms for evaluate purposed IANRA because of better results of AntHocNet in several experiments rather than others.

2.6 Summary

A wireless mesh networks and mobile ad-hoc networks support independent wireless and mobile communication systems. In MANET and some part of WMNs, a mobile user acts as a routing node. In other words, the mobile nodes in these networks are as both clients and routers. Routing protocols can be classified in several ways. In this chapter, the routing protocols for wireless networks are classified in centralized and distributed, according to their behaviour to management the routing tables and routing decision. On the other hand, the distributed routing protocols have been categorized to static and dynamic (adaptive). Afterward, in other taxonomy, adaptive routing protocols divided in to reactive and proactive types and described by given illustrations as well.

Finally, with considering the AODV as a very popular owing to its advantages, ability to stabilize the routing, its better security and its competence to apply in WMNs, make it the best candidate to compare with proposed IANRA routing algorithm in this thesis.

The next chapter presents the details swarm intelligence based routing algorithms which are related to this research work.

CHAPTER 3

SWARM INTELLIGENCE BASED ROUTING ALGORITHMS

3.1 Overview

Swarm intelligence (SI), as demonstrated by natural biological swarms, has numerous powerful properties desirable in many engineering systems, such as network routing. Intelligent swarm technology is based on aggregates of individual swarm members that also exhibit independent intelligence. Members of the intelligent swarm can be heterogeneous or homogeneous. Due to their differing environments, members can become heterogeneous swarms as they learn different tasks and develop different goals, even though at the beginning they were homogeneous [Hinchey 2007].

The ant colonies algorithm is one of the most successful experiences are based on swarm intelligence. Marc Dorigo et al. showed success with their pioneer efforts using social behaviour patterns of ant colonies to model difficult combinational optimization problems [Hinchey 2007, Dorigo 2004a, Bonabeau 1999]. The field of ant algorithm based study models are derived from the observation of real ants' behaviour. These models are used as a source of inspirations for the design of novel algorithms for the solution of optimization and distributed control problems. One of the most successful examples of ants' algorithm is known as Ant Colony Optimization (ACO) [Dorigo 2004a].

Currently there are few technically sound routing algorithms based on ACO. Therefore, this area is quite new and it is interesting for researcher to find more solutions for many concealed problems especially in routing for existing wireless communication networks. The most popular ACO-based routing algorithms which are especially designed for wireless networks (ARS, AntHocNet and etc.) have been discussed in this chapter.

In this chapter, the ACO metaheuristic is introduced and discussed briefly, and then the basic routing problems in data networks are given followed by ACO solution. These solutions can be heuristic to find the local optimum or metaheuristic to find global optimum solutions. Afterwards available and most popular routing algorithms based on ACO for data networks which are applicable for WMNs and MANET are considered with their related objectives, advantages and disadvantages. Load balancing in WMNs and ad-hoc is presented in this study followed by chapter summary in section 3.3.

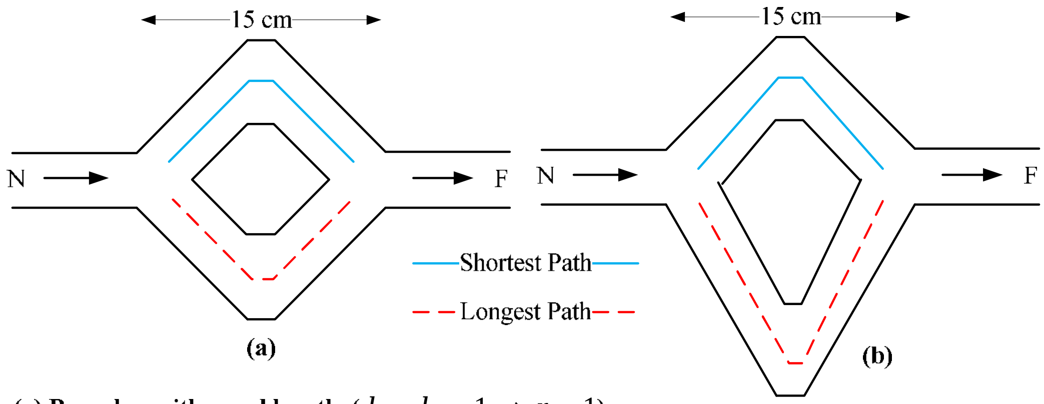
3.2 Ant Colony Optimization Algorithm for Data Network Routing (AntNet)

Solving the routing problems in data communication networks is one of the important objectives for ant colony optimization. The basic idea behind ACO algorithms for routing is acquisition of routing information through path sampling using ant agents [Dorigo 1999, Ducatelle 2004]. Routing refers to the distributed activity of building and using routing table. On the other hand, routing table is a common component of all routing algorithms. Routing table holds all needed information used by the routing algorithm to make decisions for the local forwarding. The type of this information in routing table is depending on characteristics of routing algorithm [Dorigo 2004a]. ACO based routing algorithms use pheromone table instead of routing table and it is described in next section follow by the basic concepts of AntNet routing algorithm.

3.2.1 The Basic Concepts of AntNet Algorithm

One brilliant experiment was designed and run by Goss and colleagues [Shtovba 2005, Goss 1989]. They ran experiments varying the ratio, $r = l_l / l_s$, between the length of two branches of a double bridge, where l_l was the length of the longer branch and l_s the length of the shortest one. In their first experiment (shows in Figure 3.1.a [Dorigo 2004a]), the bridge had two branches of equal length ($l_l = l_s = 1 \Rightarrow r = 1$). At the beginning, artificial ant based agents were left free to move between the N (Nest)[7] and F (Food)[8] and the percentage of ants that chose one or the other of the two branches were observed over time. Then used the other bridge with two different length of branches which are depicted in Figure 3.1.b [Dorigo 2004a] ($l_l = 2\ and\ l_s = 1, thus\ l_l \neq l_s$). When trial started there was no pheromone on any branch, so it was assumed that AntNet based agents will select the branches with equal probability. The agents deposited pheromone during the travel on the branches. Condensation of pheromone on each of branches increases selection probability by ants as usual.

[7] Nest node; which is Source Node (S) on the supposed network, thus $N \equiv S$.
[8]The Food source (F) gives a hint of destination node (D) so, $F \equiv D$.



(a) Branches with equal length $(l_l = l_s = 1 \Rightarrow r = 1)$

(b) Branches with unequal length $(l_l = 2, l_s = 1 \Rightarrow r = 2)$

Figure 3.1. Experimental Setup for Double Bridge Experiment.

In first experiment (Figure 3.1.a) the probability of path/branch selection was same depending to the pheromone congestion on each of paths. Then again, in second experiment (Figure 1.b), the length ratio between the two paths was set to $r = 2$, so that the longer path was twice as long as short one. In this case in most of trails, after some time duration all the ants chose to use only the shorter path. The obtained results in the double bridge shows: (a) for equal path length; the ants used either one of the paths with equal probability for all trails, (b) for unequal path length, in all trails the majority of ants chose the shorter path [Dorigo 2004b].

If, $P_{i\gamma}(t)$ is the probability of the ant arriving at decision spot $i \in \{1,2\}$ (see Figure 3.1.b) and selects paths $\gamma \in \{l, s\}$, also $\varphi_{i\gamma}(t)$ denote the total amount of pheromone on the path. For example, the probability of discovering the shorter path is given by Equation 3.1.

$$\rho_{is} = \frac{(t_s + \varphi_{is}(t))^{\alpha}}{(t_s + \varphi_{is}(t))^{\alpha} + (t_s + \varphi_{il}(t))^{\alpha}}, \qquad \alpha = 2 \qquad (3.1)$$

Where, α is two and $\rho_{il}(t) + \rho_{is}(t) = 1$. Now suppose μ be the number of ants cross the path per second in one direction at constant speeding of υ cm/s that depositing one unit pheromone on the way. Therefore, an ant will choose the short path traverse it $t_s = l_s/\upsilon$ seconds. This time for longer path will be $r.t_s$ seconds, where $r = l_l/l_s$. To describe the evolution of the stochastic systems, the differential equations are as follows[Dorigo 2004a, Dorigo 2004b].

$$\frac{d\varphi_{is}}{dt} = \mu\rho_{js}(t - t_s) + \mu\varphi_{is}(t), \quad (i = 1, j = 2;\ i = 2, j = 1) \tag{3.2}$$

$$\frac{d\varphi_{il}}{dt} = \mu\rho_{jl}(t - r.t_s) + \mu\varphi_{il}(t), \quad (i = 1, j = 2;\ i = 2, j = 1) \tag{3.3}$$

In the basic ACO algorithm, basic idea for routing [Dorigo 1999, Sim 2002] is the possession of routing information through the sampling of paths using small control packets, which are called ants. The ants are generated concurrently and independently at the nodes, with the task, to test a path, from Source (S) to Destination (D). The ant collects information about the quality of its path (e.g. number of hops, etc.), and uses this on its way back from D to S to update the routing information at the intermediate nodes and at S. Ants always sample complete paths, so that routing information can be updated in a pure Monte Carlo way, without relying on bootstrapping information from one node to the next [Schoonderwoerd 1996]. The routing table for each destination contain a vector of real-valued entries. One entry indicates source to destination route for each known neighbour node. These entries are a measure of advantage of going over that neighbour on the way to a certain destination. They are termed pheromone variables, and are continually updated according to path quality values calculated by the ants. The repeated and concurrent generation of path-sampling ants results, the availability of a bundle of paths, each with an estimated measure of quality, at each node. In turn, the ants use the routing tables to define the path they may sample. At each node they stochastically choose a next hop, giving higher probability to links with higher pheromone values. In the rest of the paper the routing tables are denoted as pheromone tables and vice-versa.

This process is quite similar to the pheromone laying and following behaviour of real ant colonies. Like their natural counterparts, the artificial ants are in practice autonomous agents, and through the updating and stochastic following of pheromone tables they participate in a stigmergic communication process. The result is a collective learning behaviour, in which individual ants have low complexity and little importance, while the whole swarm together can collect and maintain up-to date routing information.

The pheromone information is used for routing data packets, more or less in the same way as for routing ants. Packets are routed stochastically, giving higher probability to links with higher pheromone values. Usually, data for the same destination are spread over multiple paths (but with more packets travel over the best paths), resulting balanced load in the network. This mechanism is usually adopted to avoid low quality paths, while to make the ants more explorative, so that the good paths can be maintained and less good paths can be avoided. The path exploration is kept separate from the ongoing paths. Enough ants are sent to different destinations to make sure nodes have up-to-date information about the best paths and can automatically adapt their data load accordingly.

3.2.2 Routing Algorithm With AntNet Behaviour

In computer networks, probability of using routing tables, in all nodes in networks for routing, can act as pheromone. This probability is usually calculated with ant's traffic or packages [Sim 2002, Dorigo 2005]

Dorigo and Di Caro proposed Basic AntNet (B-AntNet) method, where the information that comes from Ants appear in each node like a routing table and a data structure which called Local Traffic Structure (LTS) with information about local traffic and delay quantities [Dorigo 1999]. Figure 3.2 shows data structures of an N-node network used in Ant-Net method where each node has 'L' neighbours [Dorigo 2004a, Sim 2002, Dorigo 2006].

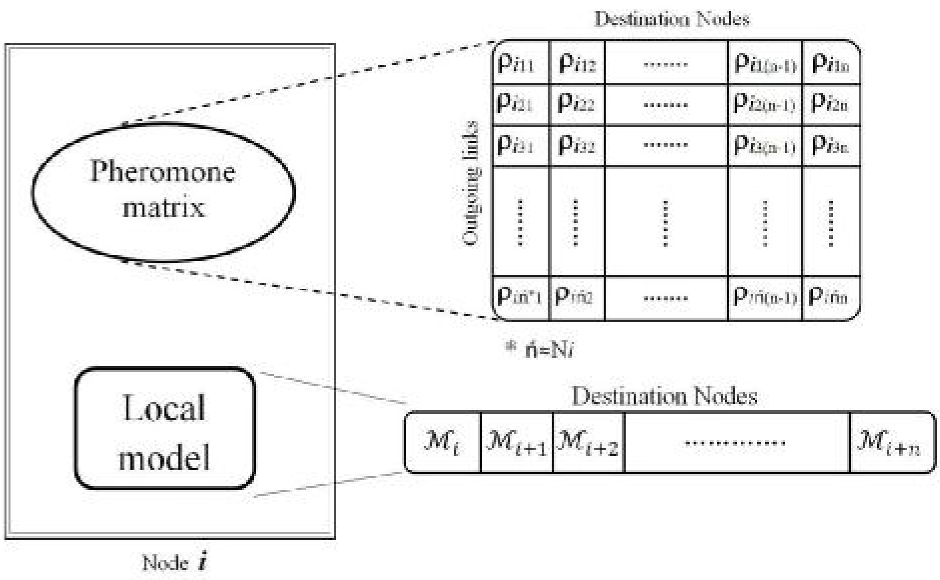


Figure 3.2. Data Structures Used By The Artificial Ants in AntNet For Case of Node i.

The nodes in the network function as routers also. To accomplish this task, they are using ants to gather information about the traffic load in the network. The traffic load depends on the amount of packets in the network (congestion level of the network).

The congestion level is proportional to the delay that a data packet experiences during the trip from its source to destination. If the congestion level is high the data packets will need more time to get to their destination. To collect the information about the traffic load on their path towards destination, the ants calculate the time that a data packet would experience using the same path. This information is used to update the two data structures in a node, which are: the Pheromone Matrix and the Local Model (Figure 3.2) statistics. The ants are able to read and write in these two structures, while the data packets are only reading information from the routing table to go to their destination. Pheromone matrix is an isomorphic local data-base that helps router to decide where to forward data packets or not. It contains the information which specifies the next (neighbour) node to travel by a data packet to go to any possible destination in the network. Each routing table is organized as a set of all the possible destinations (all the nodes in the network) and the probabilities to reach these destinations through each of the neighbours of the node which is located in next hope.

The routing tables are organized like vector distance algorithms. The local model (LTS) shows structure of local traffic plays the role of a local adaptive model for the expected delay toward each possible destination. In AntNet, two different kinds of ants were used: Forward Ant (FA) and Backward Ant (BA) as depicted in Figure 3.3.

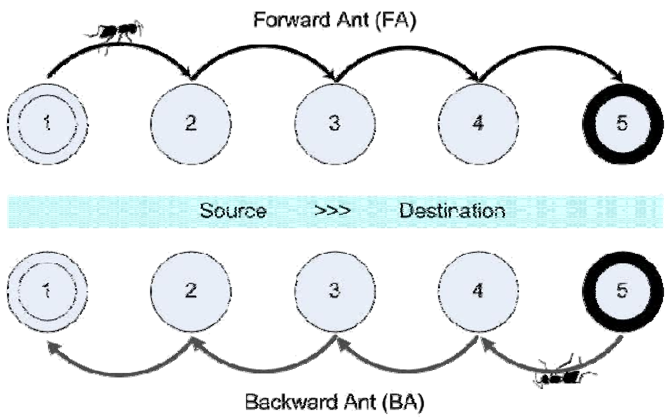


Figure 3. 1. Two kinds of ants on example of the path AntNet's ant update node data structure.

FAs are the researcher Ant that discover the new routes, evaluate the route and analyze delay. FA move from source to destination during the route and store the information of route passing time in one stack. When they arrive to their destination, produces BA and transfers to it all the information that stored during this route. Backward ants use the stacks, produced by FA, and come back to the source in reverse route then upgrade the LTS structure and routing table for all nodes.

The quantity of $\rho_{j,i}$ in pheromone matrix (routing table) calculated as follows: if only one ant arrive (from node i) to node j, the probability of choosing that route will be increased base on Equation 3.4. In addition, probability of connective route to other nodes will be decreased base on Equation 3.5, because the probability table must be normal [Dorigo 2004a, Dorigo 2005, Dorigo 2006]. Finally, Equation 3.6 is correct for all columns in the probability table in Fig 3.2. $\Delta\rho$ in Equations 3.4 and 3.5 shows the effect of ant movement at the entrance of probability table.

$$\rho_{j,i} = \frac{\left((\rho_{j,i})' + \Delta\rho\right)}{(1 + \Delta\rho)}, \quad (\rho_{j,i})' = \rho_{j,i}(OLD) \tag{3.4}$$

$$\rho_{j',i} = \frac{(\rho_{j,i})'}{1 + \Delta\rho}, \qquad j' \neq \ and \ j' \in \{Neighbours\} \tag{3.5}$$

$$\sum_{j=0}^{n} \rho_{j,i} = 1, \quad where\, j \in [1, \dots, n], \ \ L_n = \{neghbours\ (n)\} \tag{3.6}$$

One of the most important problems that exist in this routing algorithms with ants' colonies is statistic route and not adaptive as per need in the network [Oida 2000, DiCaro 2005]. Statistic means that after ants choose the $\Re_{O.P}$ route as optimum route, the inclination of other ants to choosing this route is usually increased. This causes traffic congestion due to increased traffic and at the same time the probability of use of other routes will be decreased. Choosing $\Re_{O.P}$ as only one optimum route in network may create other problems such as heavy congestion in selected optimum path. Therefore, selected $\Re_{O.P}$ will be come back to non optimum route again.

To solve this statistic nature route problem, Multiple Ant Colony Optimization (MACO) [Baran 2002] used different ants with their special pheromone instead of using one kind of ant. In MACO, each kind of ant can find the separate optimum route and this increase route adaptation and solve the statistic route problem [Dorigo 2004a, Dorigo 2006, Baran 2002]. In addition, Bonabeau et al. have showed success of ants when they act as gregarious to find the shortest route is proportional [Bonabeau 1999]. Here, it is seen that, if a group of ants choose non-optimum route ($\Re_{N.O}$), by mistake, the other ants will choose and follow the same $\Re_{N.O}$ at the end. The concentration of pheromone will be increased and the $\Re_{N.O}$ will be used as optimum route. Therefore, non-efficient routing can be created.

The proposed IANRA attempts to decrease the probability of choosing non-optimum route instead of optimum one by more searches among possible routes. Also, instead of using one optimum route, IANRA try to find and use, several optimum (or sub-optimum) routes to solve the congestion problems caused by a single optimized route.

3.3 Summary

One of the most successful examples of ant algorithms is known as Ant Colony Optimization. The framework of ACO is based on swarm intelligence theory. ACO is inspired by foraging behaviour of real ant colonies, and targets discrete optimization problems. The basic idea behind ACO algorithms for routing in data communication networks is the acquisition of routing information through path sampling using ant agents. On the other hand, network routing is a difficult problem because of its stochastic and time-varying nature. In AntNet based routing algorithms, the routing tables called pheromone tables. All the nodes in the network try to keep information of this table up to date to make better decision about next hop to forward the packets. For up-to-dating the information in the pheromone table, there are several methods which proposed by authors of AntNet based routing algorithms. The basic idea behind S-ACO algorithm for routing algorithm is to find the shortest path between source (nest) and destination (food) or vice versa.

Among few ACO framework based routing algorithm e.g., S-ACO, ARS and AntHocNet, only some of them support quality of service requirements. Currently AntHocNet is one of the AntNet based routing algorithm that is proposed for mobile ad-hoc networks. AntHocNet is given better results rather than other ACO framework based algorithms. However, AntHocNet is less efficient in terms of routing overhead. By considering advantages of AntHocNet, it has selected as one of reference algorithm to evaluate proposed IANRA routing algorithm by comparison behaviour of aforesaid algorithms on wireless mesh and mobile ad-hoc networks.

The next chapter presents the method and structure of IANRA algorithm with associated parameters.

CHAPTER 4

METHODOLOGY

4.1 Overview

This chapter presents the methodology of the current research on Intelligent AntNet-based Routing Algorithm (IANRA). The chapter is organized as follows. Section 4.2 gives the introduction to the IANRA. The algorithm design aspects and simulation environment are presented in Section 4.3 and 4.4 respectively.

4.2 Introduction to the Intelligent AntNet based Routing Algorithm

The main idea behind IANRA routing algorithm is to use several types of researcher ants for several purposes. One particular type of ants is used for one specific type of services in the network. Therefore, to achieve a complete optimum and sub-optimum routing table (pheromone table), several kinds of ants are used for each node. Each generation of FA are able to increase own generation after arriving to a node. In this algorithm, the used ants produce new generation and new generation get the paths and pheromone table information as inheritance. In routing process when an ant from a particular family arrives to a junction node with n different connective paths to the neighbours, the ant regenerates n successive ants and then sends them one per each connective paths accordingly based on same considered criterion. On the other hand, these new generations of ants inherit identifier of their family, the generation numbers and the routing information from their parents that includes route delay, bandwidth and identification of visited nodes. For route discovery purpose, when the different generations meet each other in any junction node, old generation is allow to continue crossing the paths to destination. In the path discovery phase of IANRA in this chapter, this matter has been discussed in details.

Hence, IANRA algorithm applied into two wireless networks to evaluate its behaviour on different network topologies. Figure 4.1 shows the brief methodology block diagram. The following section discusses about path discovery, route maintenance and handling link failure phases of IANRA algorithm in details.

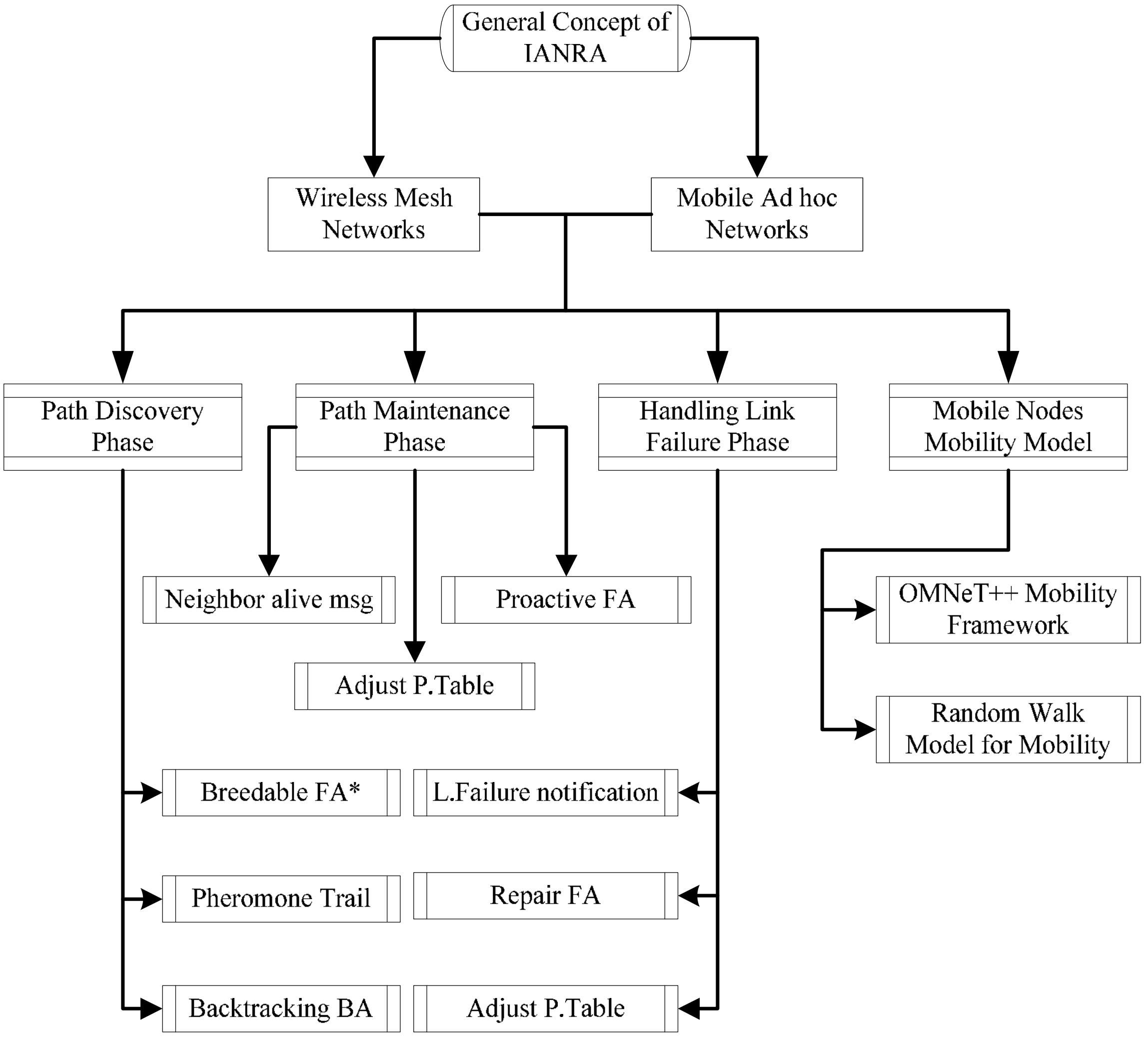


Figure 4.1. IANRAs' Methodology Block Diagram.

4.3 Design Aspect of IANRA Algorithm

IANRA routing algorithm is designed as a hybrid algorithm, because it contains both reactive and proactive factors. In the optimum path discovery phase the algorithm use reactive forward ants that they only collect routing information from source node to the destinations. On the other hand, IANRA acts as proactive when the algorithm tries to maintain and up-date information about existing possible paths. Like all available routing algorithms based on ACO, in IANRA algorithm, routing information is stored in pheromone tables.

4.3.1 Path discovery phase

One of the important parts of all routing algorithms is path discovery phase. On the other word each routing algorithm use own especial algorithm to setup optimum path. For example AODV routing algorithm used Hello, RREQ and RREP message to monitor neighbours' nodes and discovering the optimum route as well. After setting up available optimum rout, every node should know about mentioned paths to use it as an optimum route for data transferring.

All of swarm intelligence base routing algorithm tries to follow the real behaviour of swarm like ant colonies. As mentioned in chapter three, AntNet is even closer to the real ants' behaviour that inspired the development of ACO metaheuristic than the ACO algorithms for NP-hard problems. Currently all of AntNet based routing algorithm is conventionally described in terms of two sets of artificial ants called in the following Forward and Backward ants.

IANRA routing algorithm uses the ants which are able to produce new generation and breeding for path discovery purpose. Usually the available nodes in a networks are divided into three groups; source, intermediate and destination nodes. Source node is the node which is going to send packets to distinct destination and all of the nodes which support the packets to forward to destination are called as intermediate nodes.

For starting the procedure of path discovery in IANRA routing algorithm, source node must generate the first generation of forward ant and broadcast it to all existing neighbour nodes. Main duty of FA is cross intermediate nodes and reaches to destination node. When FAs arrive to Intermediate Node (IN), at the first step IN will track the reached FA and its generation number in local data structure. Among reached FAs in an intermediate node, the old generation FA is allowed to continue crossing paths in order to obtain shortest path to the destination. On the other hand, the younger generation of FA will be killed in intermediate node to hold back crossing.

After selecting the old generation to continue the trip, Time To Live (TTL) of FA is checked in intermediate nodes. If the TTL reached for a FA, it should die in the visited intermediate node otherwise FA has to generate new generation of FAs to go on and forward to the next hop. A parent FA is bequeathing entire passing paths information to its generation. During forwarding, the local pheromone table must be update then the new generation of FA is able to forward to available neighbour nodes. The mentioned scenario will be continuing until the FAs' generation arrive to the destination node.

If few generations of parent FA reach to a destination, all the receive FAs from same source node are compared to select the oldest generation. After selecting a right FA, it should kill FA and generate Backward Ant (BA) and send it to source for back-tracking the same path crossed by selected FA.

While BA crossing the reverse path, pheromone table of each intermediate node which located on aforesaid path will be updated. When source node received the BA, it makes up-to-date the local information of source node about the available paths.

By updating the pheromone table in the source node and intermediate nodes, reverse path is choose as a shortest and optimum path.

For choosing the near optimum path in this algorithm, the 2nd and/or 3rd oldest FAs which reached to the destination can generate BA there and send it to backtracking trough intermediate nodes. If reverse path is made successfully by receiving BA by the source node then this path will be select as a near-optimum path for routing algorithm. In the pheromone table mentioned path will be as a reserve path and whenever congestion is occurred in the network, the algorithm can choose near-optimum paths for load-balancing purpose in the network.

Figure 4.2 shows the main idea of IANRA for path discovery phase and to setup optimum path in the network. In this figure, behaviour of IANRA algorithm is shown for three groups of existing nodes (source node, intermediate nodes and destination node) in the wireless networks.

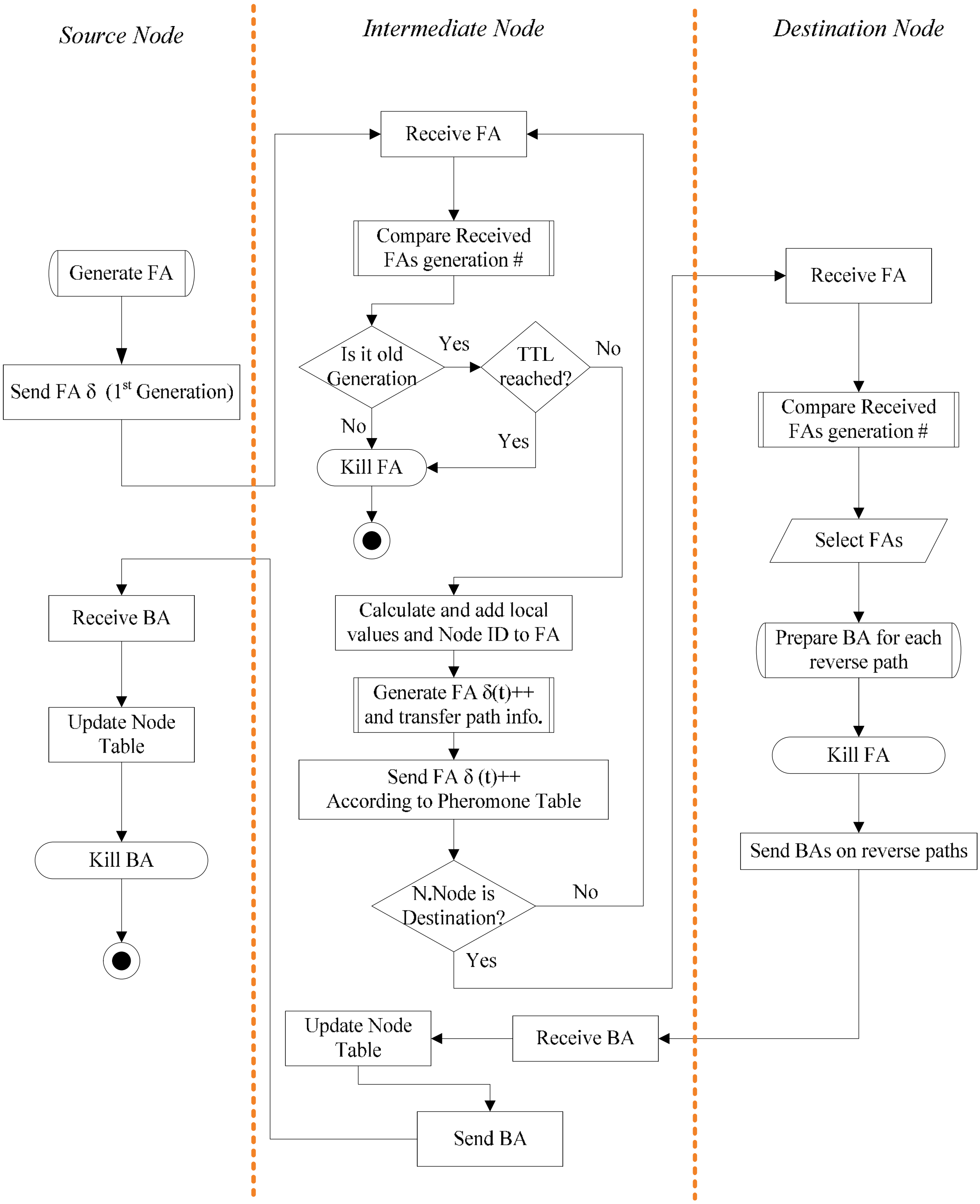


Figure 4.2. Flowchart of Path Discovery Phase Algorithm by FAs

Figure 4.3 shows the outgoing link from source node (S) with $k = 1$ generation number of Forward Ant (FA). Here, $FA\ [k]$ and $FA\ [k + 1]$ are denoted kth and k+1th generation of forward ants accordingly. When $FA\ [k]$ arrive to the N_i as intermediate node then start to make new generation and forward it to the other neighbour nodes. This procedure is continued until the first packet from source node arrives to the destination. In contrast, if some of the intermediate nodes received several incoming packet with different generation numbers from same source for path discovery purpose, the intermediate nodes should be able to decide about right generation for breeding and packet forwarding.

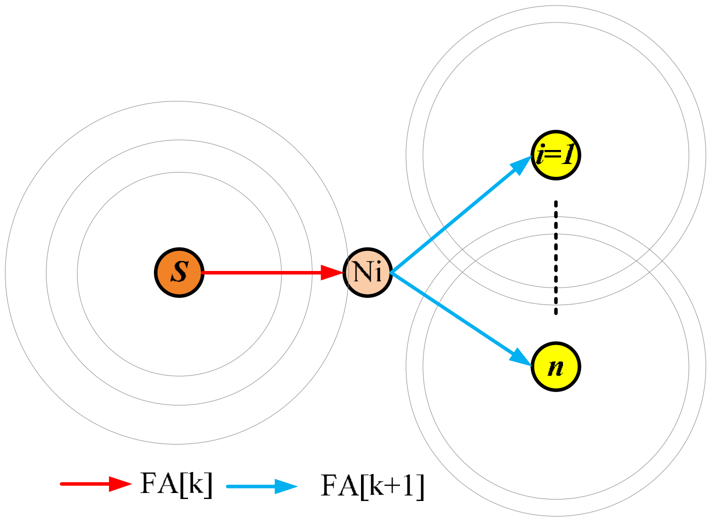


Figure 4.3. Generate and Forwarding FA to The Neighbours' Node at Intermediate Node Level

Figure 4.4 depicts very simple example that shows how the intermediate nodes can decide about the forwarding of ant generation. In this picture, two different packets forwarded to node N as FA [x+1] and FA [y+1]. In this case, node N should select the younger generation, FA [x+1] if $x \leq y$ and let it Crosse the next paths. By applying this algorithm and using aforesaid decision in all intermediate nodes, the mentioned algorithm is able to guaranty that arrived packet from source node cross minimum number of available hops from source to destination and set the pheromone table via several generation's information during the crossing available paths on network.

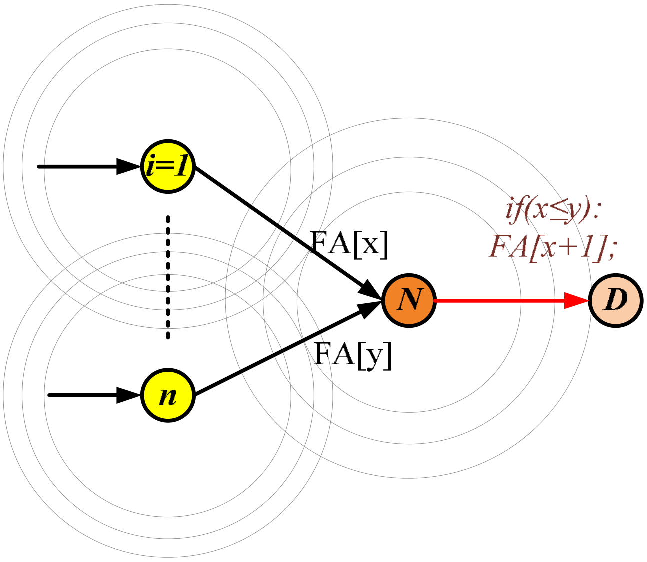


Figure 4.4. Forwarding the Different Generation of FA to Destination Through Intermediate Node

Let i and j be nodes in network and FA generations numbers respectively, which are located on selected optimum path and t denoted service time per node. Then the amount of travelling time for FAs to travel each of the selected path (x) from S to D is;

$$\xi = \sum_{i=1}^{n} \tau_i + \sum_{j=1}^{m} \xi_j \tag{4.1}$$

$$Node's\ number\ on\ selected\ path, i = \{1, 2,3, \dots , n\}$$

$$Number\ of\ generations, j = \{1, 2, \dots , m\}$$

Figure 4.5 shows a sample of path discovery by several generations of FAs. The circle in Figure 4.5 shows one of the intermediate nodes, when second and third generations of FA arrive to N_i (intermediate node), the oldest generation will select to continue the rest paths to the destination. So the third generations which are marked by green colour should die and second generation is allowed to extend path discovery. Then the second generation of FA generate third generation and forward it to the available neighbours. In the N_i three FAs from fourth generation try to backtracking but this algorithm dose not allows the FAs to do backtracking. Finally, three generations of FAs have reached to destination. The oldest generation's (4^{th} generation) path is selected to send BA on reverse path. If the BA reaches to the source node successfully, a reverse path will be select as an optimum path in the network. The next two oldest reach FAs' generation to the destination are used to generated BA to send it to the destination for creating near-optimum paths in similarly way.

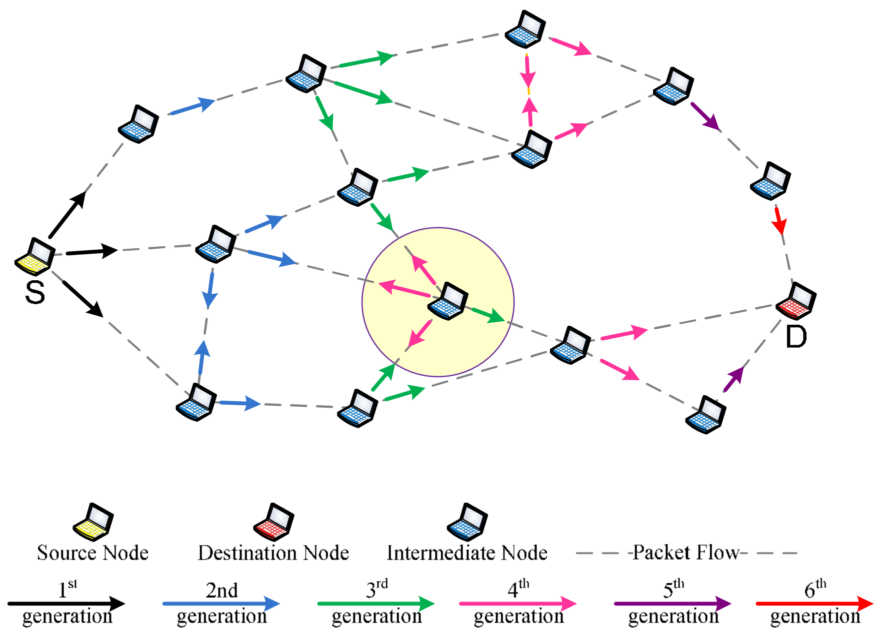


Figure 4.5. Sample Distribution of Intelligent Forward Ants to Setup Optimum and Sub-optimum Paths.

4.3.2 Proactive Route Maintenance

One of the important parts of the each network routing algorithm is to try to update the information about the currently used paths to the destination, and at the same time tries to discover new and better paths.

In IANRA routing algorithm during the course of communication session, a source node tries to keep update all information of available optimum and near-optimum paths to the destination proactively. Also proposed algorithm tries to find new and better paths to enhance behaviour of networks for data communication. “Hello messages” is played main and certain role in that process. Hello messages are short messages and they broadcast every τ_{hello} second. This message broadcast by all exist nodes in the network. Most popular routing algorithms use this kind of message to keep updates their neighbours’ information on each node. As an example, when node i received hello message from a new a node j, it can suppose that j is its new neighbour. After registration j as a one of the neighbour for i, it presume to get hello message from j every τ_{hello} second. After receiving hello message regularly from j, if some expected hello messages missing from j, node i assume that the node j has moved out of coverage area and node j will removed from neighbour information on node i.

Here, in IANRA, all the nodes include in the hello messages they send out their routing information about their active destinations. For this matter, a node j creating hello message according to its pheromone table and picks a maximum number of active destinations (k). For each one of selected destinations (d), hello message contains the address of d and the best available value of pheromone (ρ_{m*d}^{n})

according to the pheromone table. In mentioned pheromone value, $m* \in \mathcal{N}_d^n$, which n has been available for d.

Figure 4.6 shows flowchart of maintenance part for IANRA algorithm. According to the flowchart node j received broadcast hello message from node i, then node j is decided about node i , if node i is in its neighbours list, the communication session will be continue. For continuing they send hello message at mentioned time to each other to keep up to date their neighbour information. Otherwise, if node i was not in node j neighbour list, it should register as a new neighbour to node j. By registering node j as a new neighbour, one-hop routing path will be add in node and it goes to trough the list of available destinations reported in hello message.

For each destination d, which exists in the list of destinations, it uses the received pheromone value ρ_{m*d}^n to build up a new estimate for the goodness of going from i to d via adding cost of hopping from i to j. This new estimate is called "boostrapped pheromone" $\mathcal{B}_{jd}^i$ [DiCaro 2005]. For calculate $\mathcal{B}_{jd}^i$, first of all value of ρ_{m*d}^n should be invert since pheromone has the dimensions of an inverted time and then add the estimated time to perform the single hop from i to j. Therefore, the value of $\mathcal{B}_{jd}^i$ is calculable via Equation 4.2 [Dorigo 2004b].

$$\mathcal{B}_{jd}^i = \left((\rho_{m*d}^n)^{-1} + \frac{\hat{T}_j^i + T_{hop}}{2} \right)^{-1} \tag{4.2}$$

According to the Equation 4.2 for estimate value of $\mathcal{B}_{jd}^i$, value of ρ_{m*d}^n is needed for destination. If node i already has this value, this means that there is a path from i to d over j which has been sampled completely by at least one of forward ants. Therefore this path can be considered as a reliable path. After considering aforesaid path as a reliable path, the value of $\mathcal{B}_{jd}^{i}$ should be replaced by ρ_{m*d}^{n} and then information of path should update by keeping the pheromone on current paths.

Otherwise, if i has not a value of ρ_{m*d}^{n}, the $\mathcal{B}_{jd}^{i}$ can indicate a possible new path from i through j to d. Then it can include the boostrapped pheromone in its routing table as a new entry and add it in its own hello message for further hello message broadcasting. This forwarded pheromone information is estimated based on other node's estimate and could be unreliable. Considering the old and new routing information in bootstrapping system can easily lead to loops. So, according to the dynamic environment of mobile ad hoc networks and wireless mesh network, cause of mobility, all nodes can send only boostrapped information in hello message periodically. So, i should not use $\mathcal{B}_{jd}^{i}$ to update the regular pheromone table. For that reason, $\mathcal{B}_{jd}^{i}$ is stored in a second pheromone table at i which called "virtual pheromone table" $(\mathcal{V}^{i})$. By this policy in proposed algorithm, the information of $\mathcal{V}^{i}$ can forwarded as $\mathcal{B}_{jd}^{i}$ in hello message.

If the best virtual pheromone is significantly better than regular pheromone, for evaluating the path, proactive forward ants is sent to the destination. The behaviour of proactive ants is same as reactive forward ants, but, they never broadcast. All proactive ants are sent unicast to destination through intermediate nodes. During the travelling to the destination by proactive forward ants, if they are not successful to find pheromone on the paths, they should discard. It may cause of wrong path selection or evaporation of pheromone on the path. Conversely, if proactive forward ant reached to destination successfully, it should be generate BA and send it on reverse path.

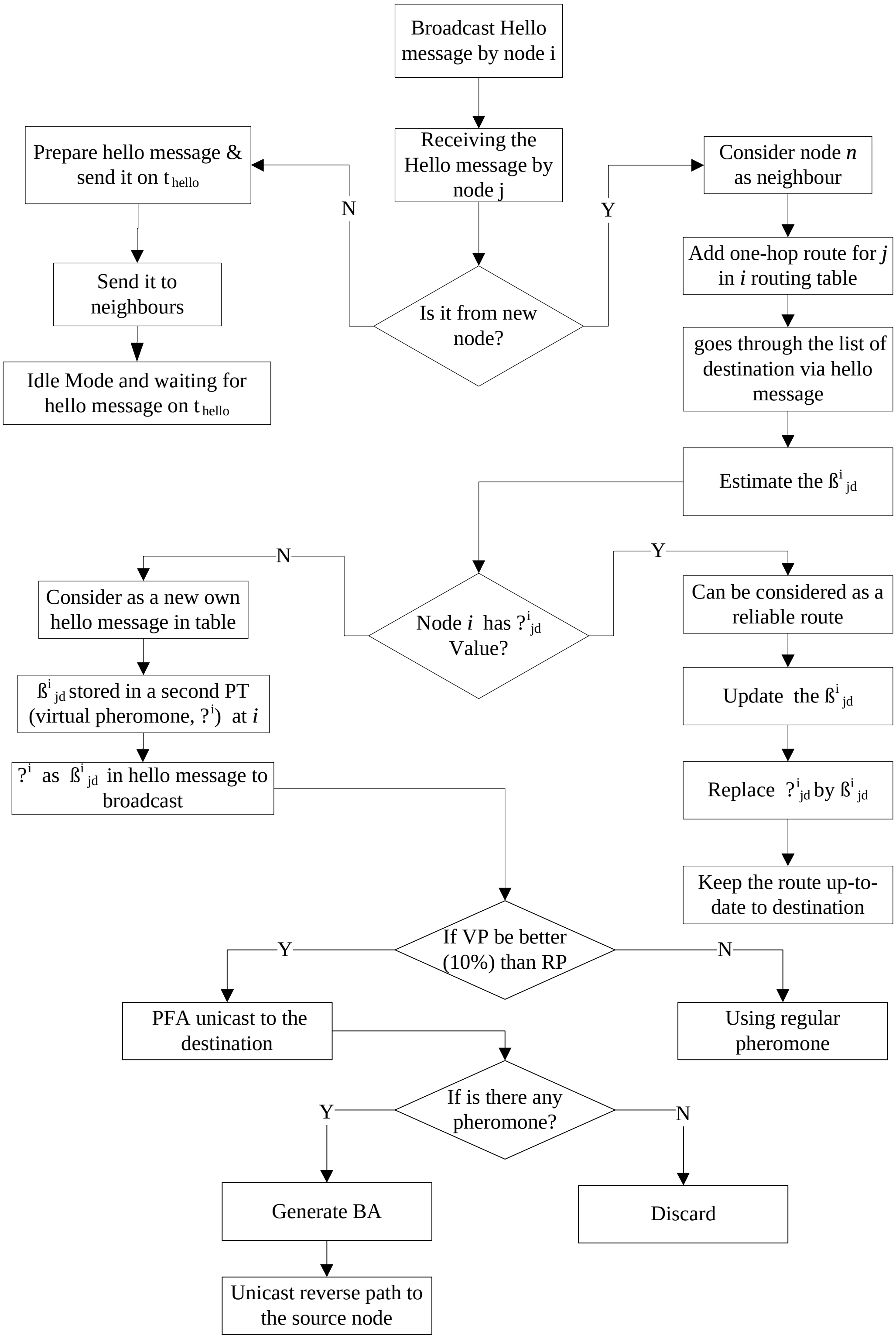


Figure 4.6. Flowchart of Proactive Route Maintenance in IANRA Routing Algorithm.

4.3.3 Handling of Link Failure

In the network, nodes can detect link failure when expected hello message were not received or transmission of ants (or data packets) fail. Most of the link failure in the networks is cause by nodes mobility and when the neighbour nodes move far away.

One of the important phases of IANRA routing algorithm is handling link failure. When any node has detected failed message during the transmission, according to the IANRA link failure policy, it should be try to solve that problem in the network immediately. Figure 4.7 shows a brief flowchart of IANRA algorithm for handling link failure in the network. Under normal conditions entire nodes on a network try to send and receive data or hello packets to each other. When link failure is occurred in the networks means a source node cannot send or forward the packet to the next hop successfully. Thus, affected node at the first step should keep a copy of forwarded packets (only data packets because hello message is not important here) in the own buffer and then remove the corrupted link information from local pheromone table. After removing mentioned information from pheromone table, entire neighbours of affected node will inform about the matter by sending the Link Failure Message (Figure 4.8) and data packets send back to the previous node to forward to the source node by using alternative paths.

When Link Failure Message (LFM) received by neighbour nodes, they start searching the available paths instead of corrupted one to the same destination. If the searching result was successful, the node can replace new path information in the local pheromone table and keep up to date mentioned table. Otherwise if the searching result was not successful and it cannot find any paths to the same destination, the corrupted link information should remove from local pheromone table. In any case, the latest and updated information of pheromone table must send to the available neighbour nodes via next hello message.

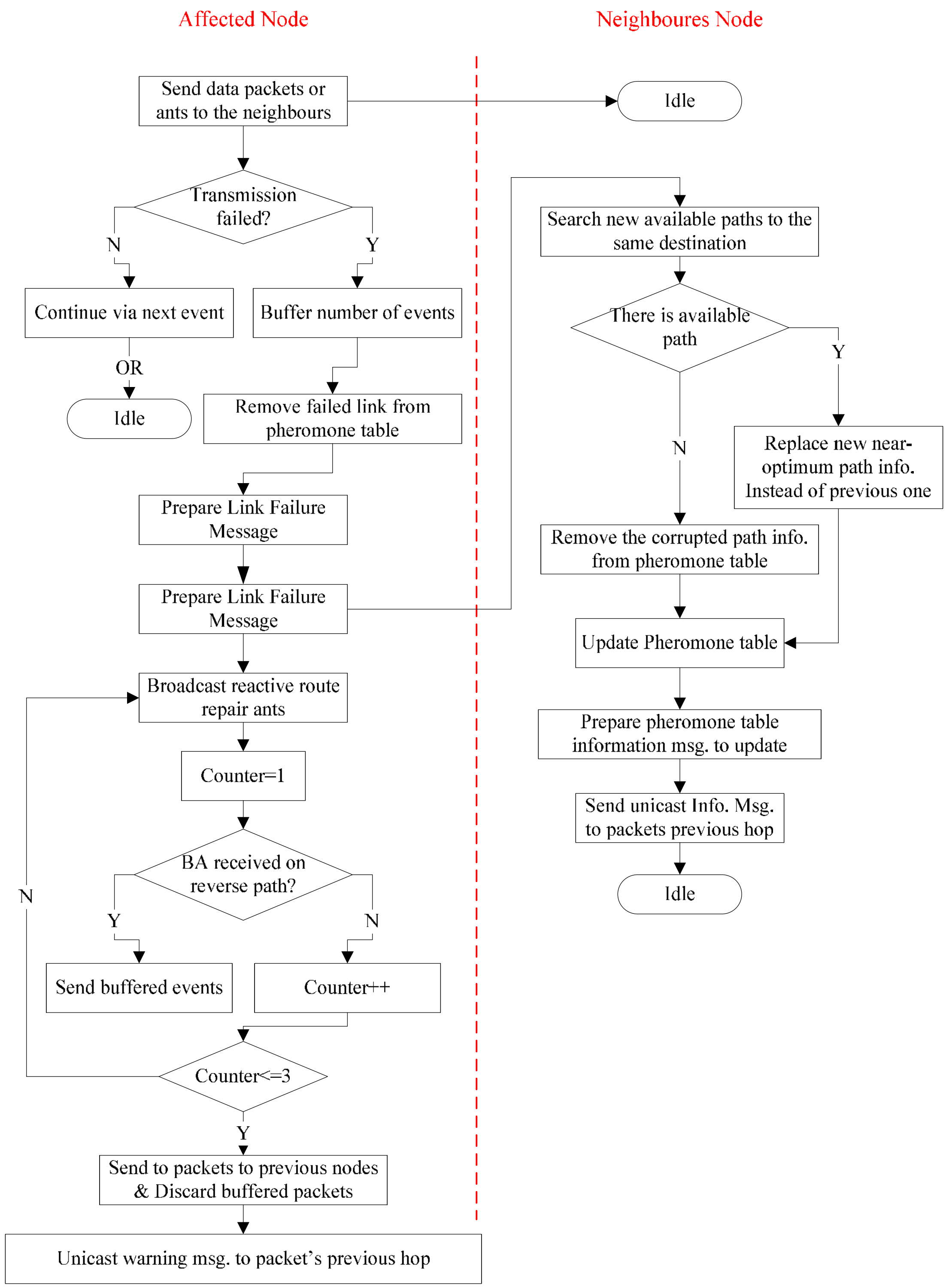


Figure 4.7. Flowchart of Link Failure Handling by Affected Node in IANRA Routing Algorithm.

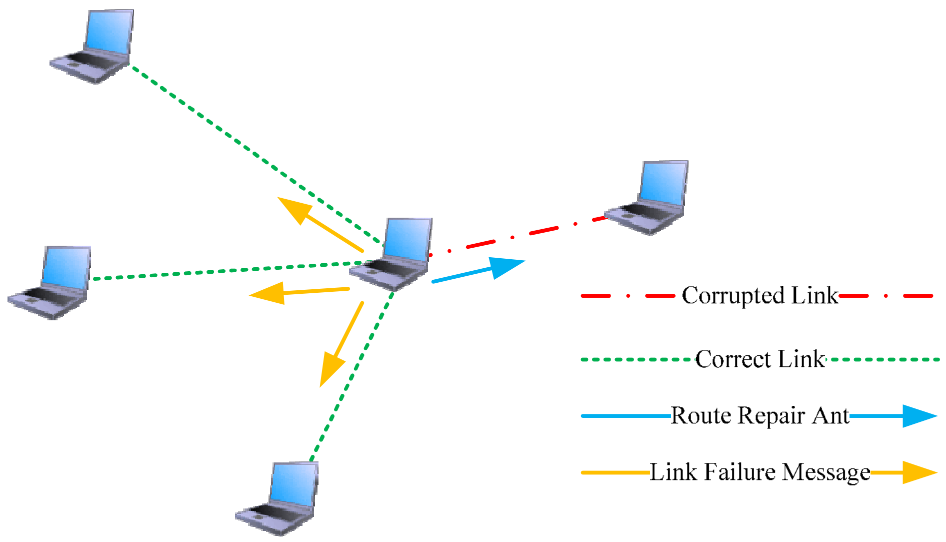


Figure 4.8. Broadcasting Link Failure Message and Sending Reactive Route Repair Ants by Affected Node.

In this case, the target of algorithm is not limited to send the LFM message only, but IANRA try to solve the corrupted link problem. After sending the message to entire available neighbour nodes, affected node will broadcast Reactive Route Repair Ants (RRRA). Perhaps RRRA can repair the occurred problem, of course if the broken node is still in signal coverage area of affected node.

Affected node after broadcasting the RRRA for repair broken link is waiting to receive Backward Ant (BA) via corrupted link. RRRA has three times (according to IANRA simulation) opportunity to send back their BA. Contrarily, all buffered data packets will be discarded from the local buffer on affected node.

4.4 Simulation Environment

For evaluation of proposed algorithm, OMNeT++ descript event simulator is used [OMNeT++]. OMNeT++ is a public-source, component-based, modular and open-architecture simulation environment with strong Graphical User Interface (GUI) support and an embeddable simulation kernel. Its primary application area is the simulation of communication networks and because of its generic and flexible architecture, it has been successfully used in other areas like the simulation of information technology systems, queuing networks, hardware architectures and business processes as well.

Figure 4.9 gives an overview of the process of building and running simulation scenario by OMNeT++ 3.3 edition [OMNeT++].

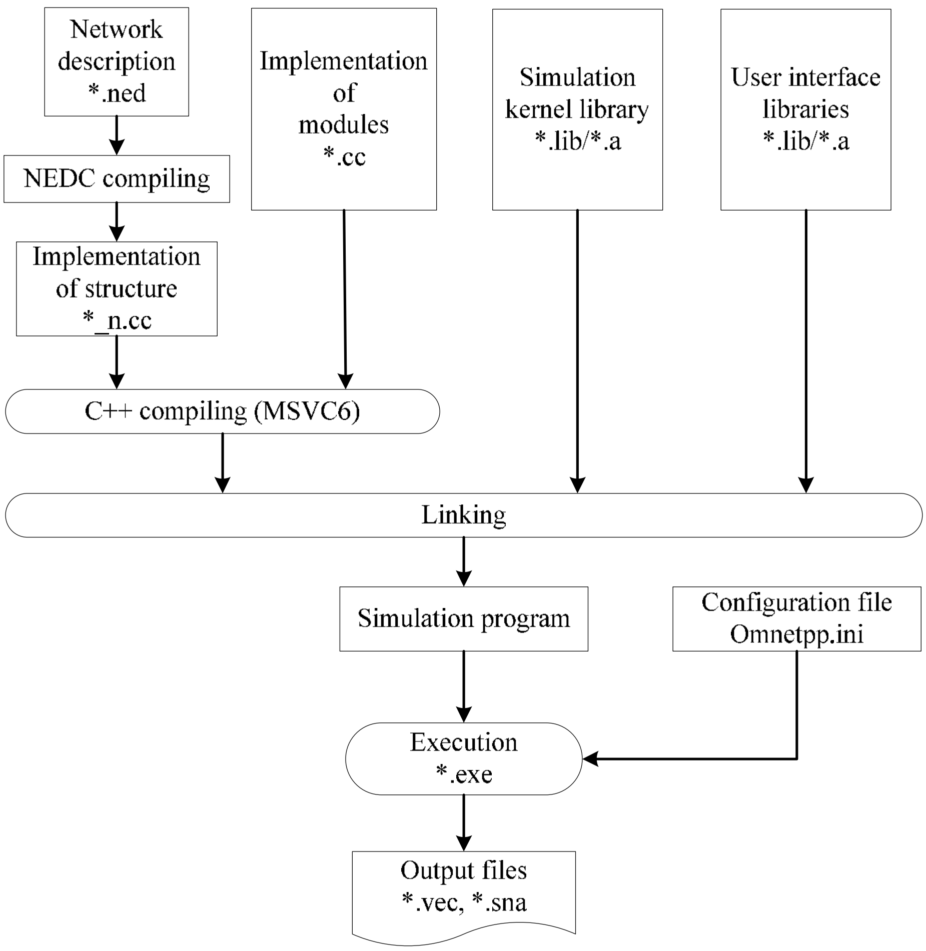


Figure 4.9. Overview of the Process of Building and Running Simulation Scenario by OMNeT++

The considered simulation area is 1500x1000m^2 and the mobile agents are moved freely in this area. In different circumstances, for mobility model of mobile nodes in both mesh and ad hoc scenario, Random Walk model is selected. Mobility models represent the mobile behaviour of nodes in ad hoc or wireless mesh networks. A mobility model should attempt to mimic the movement of real mobile agents. Random Walk model is a simple mobility model based on random direction and speed. As shown in Figure 4.10, there are six kinds of mobility models in Mobility Framework of OMNeT++ simulator and only Random Walk mobility model is enable in simulation configuration file which called “omnetpp.ini”.

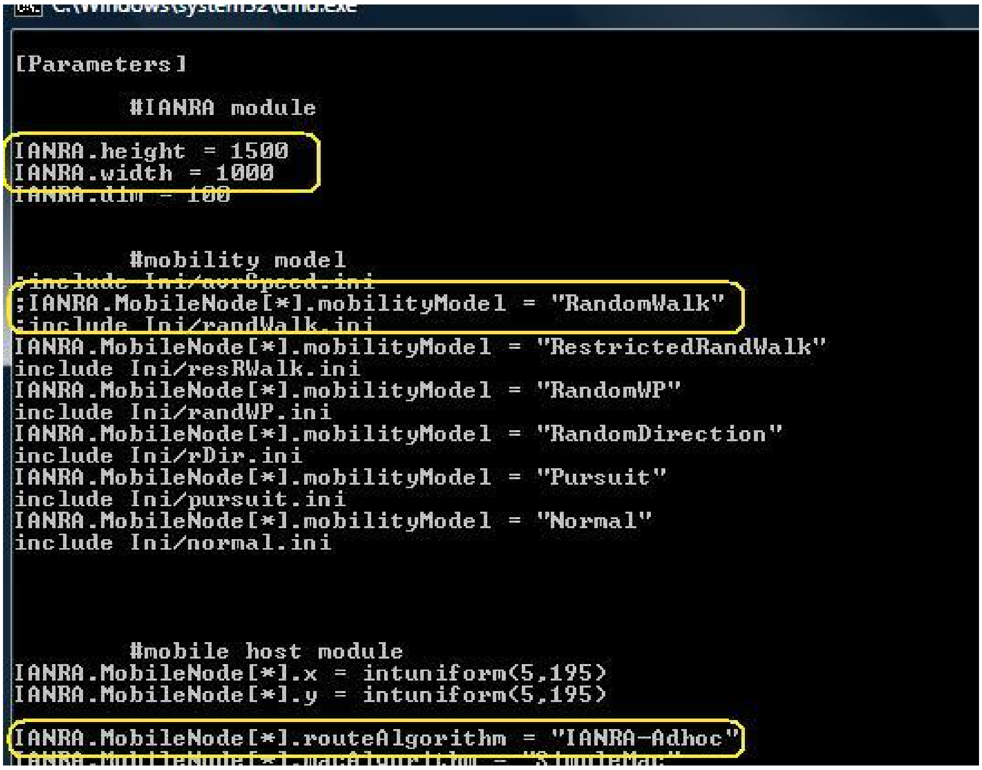


Figure 4.10. Sample of ‘omnetpp.ini’ Configuration File for IANRA Scenario

4.4.1 The Communication Networks Model for Proposed IANRA

The main communication network model of IANRA is divided into two parts: wireless mesh networks and mobile ad-hoc network. In MANET, there is not any specific infrastructure between the wireless nodes. All of the nodes in this topology try to find the neighbours nodes in their own coverage area to start data communication. After, making the connection via neighbours, they begin to discover optimum and suboptimum paths to the destination reactively, which is described in subsection 4.4.1 in this chapter. During the communication session, the IANRA algorithm tries to improve the existing optimum paths proactively.

The second topology for IANRA evolution is WMNs. In this topology, two types of nodes are used which are mesh clients and mesh routers. To make connection for data transmission, all the wireless nodes in this topology should be connecting to the closer access point. The access points are responsible for packet routing. The details is presented in section 4.3.3

4.4.2 IANRA in Mobile Ad-hoc Networks (IANRA-MANET)

First scenario for evaluation of IANRA-MANET algorithm is mobile ad hoc network scenario. In IANRA-MANET scenario 100 mobile nodes are considered, which are moving freely in the simulation area. As in MANET there is no fixed infrastructure, all of the mobile nodes are placed randomly within the simulation area. The speed of mobile nodes is considered 0 to 15 meter per second randomly. Subsection 4.4.4 describes the internal structure of each mobile node in details.

At the beginning of simulation there was no connection among the mobile nodes and their neighbours. After few second all the mobile nodes started to move and send Hello message to set own neighbours information.

After initializing the network and setting neighbours information in the mobile nodes, simulation entered to the path discovery phase to find optimum and near-optimum route between source and destination nodes. At the same time route maintenance and handling link failure phases tried to keep routing information up-to -date in the network.

Figure 4.11 shows MANET simulation environment with instant connecting neighbours in OMNeT++.

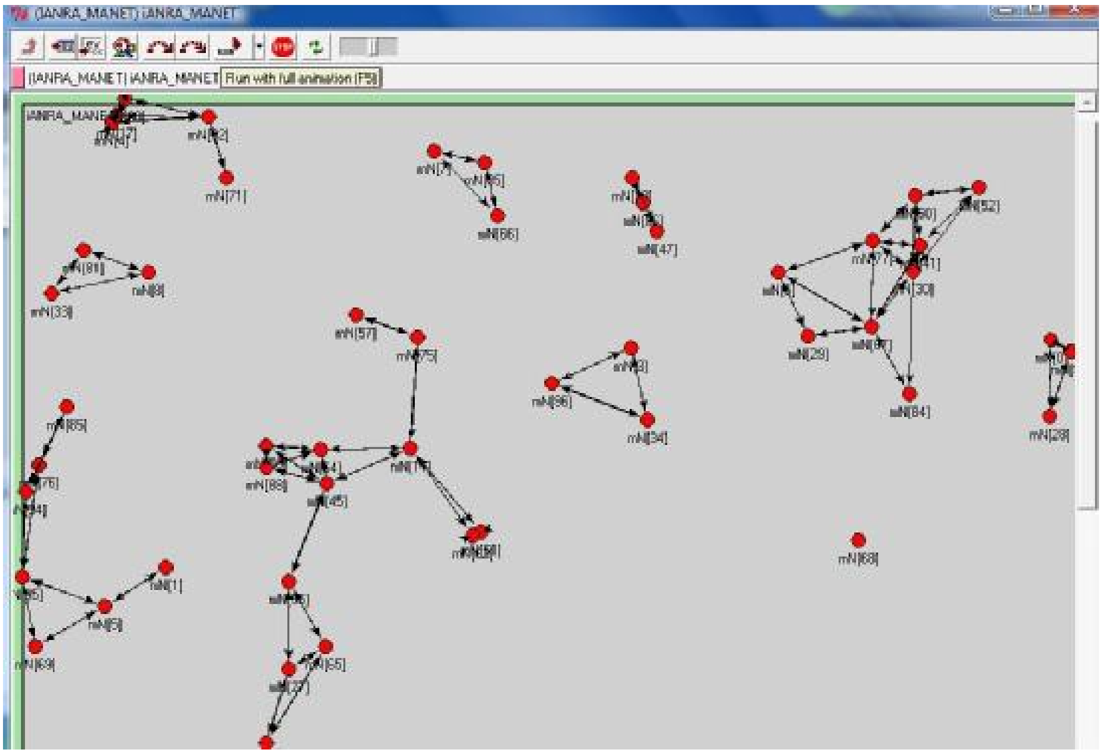


Figure 4.11. Sample of Simulation Environment of IANRA-MANET Scenario.

4.4.3 IANRA in Wireless Mesh Networks (IANRA-WMNs)

In IANRA-WMNs scenario all mobile nodes are considered same like IANRA-MANET scenario. Here, 10 fixed wireless Mesh Routers (MR) are used to keep connection among all 100 mobile nodes (mN). If some of the mobile nodes fail to be connected directly to MR, can be connected to the one of via some intermediate node. In IANRA-WMNs scenario the mobile node which is located between other mobile node and mesh router is called intermediate node.

Figure 4.12 depicts a sample simulation environment of IANRA-WMNs scenario in OMNeT++ discrete event simulator.

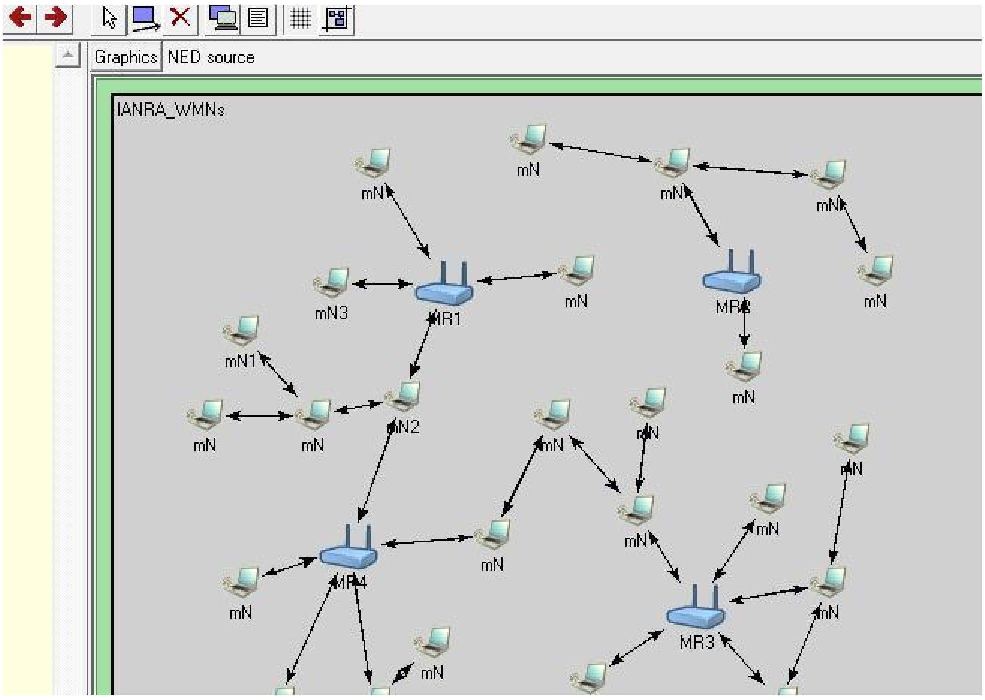


Figure 4.12. Sample of Simulation Environment of IANRA-WMNs Scenario

4.4.4 The Mobile Agents

To design the mobile nodes in OMNeT++ simulation software, we relied on sample mobile host which developed by OMNeT++ under 'ad_hoc_sim' scenario. In this design of mobile node Physical, MAC, Routing (Network) and Application layer were considered as most important layers. Figure 4.13 shows the structure of mobile nodes in OMNeT++.

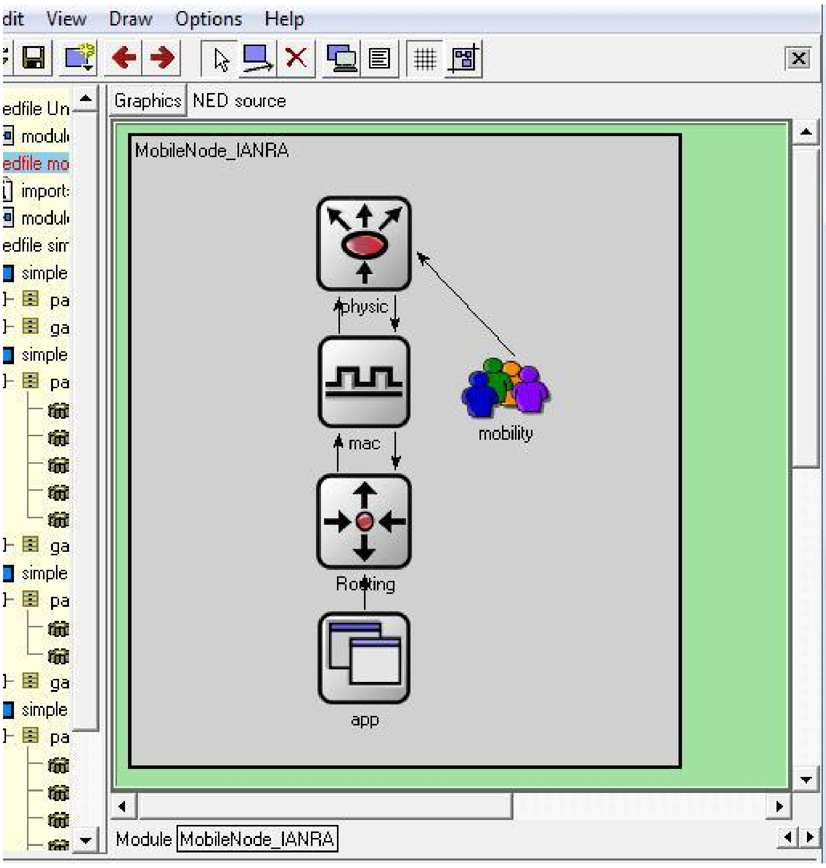


Figure 4.13. Structure of Mobile Nodes in IANRA Scenario on OMNeT++ Simulator

In simulation scenario each layer of mobile nodes are used specific parameters. The mentioned parameters type may define as a numeric, Boolean and etc. As an example in the application layer, packet size and rate values are defined as a numeric value, also Promisque mode in MAC layer has been defined as Boolean value because it is depend to the return value from MAC function source code. On the other hand, all gates in the layers should be specified in simulator software. In the gate field, incoming and outgoing links should be distinct. Table 4.1 shows more details about used parameters and gates for each layer in mobile node structure which are provided by OMNeT++ discrete event simulation system.

Table 4.1. Parameters and Gates of The Layers for Mobile Nodes of IANRA

	Parameters	Gates
Physical Layer (PHY)	Tx Power, Rx Threshold, Channel Delay, Channel Datarate, Channel Error	From mobility (in), From MAC (in) To MAC (out)
MAC	In buffer Size, Promisque Mode	From PHY (in) From Route (in) To Route (out) To PHY (out)
Routing	-	Frome MAC (in) From APP (in) To MAC (out)
Application (App)	Rate, Packet Size, HostNum, Active, Burstinterval (times between two data bursts)	To route (out)

In the next subsection, applied mobility model of IANRA routing algorithm for both MANET and WMNs scenarios is discussed. Besides, Mobility Framework (MF) [OMNeT++ 2008] is a framework to support simulations of wireless and mobile networks within OMNeT++ which is introduced in next subsection as well.

4.4.4.1. Mobility Model of Mobile Agents

As a mobility model for both MANET and WMN scenarios of IANRA, two dimensioned (x and y) Random Walk mobility model was used. Random Walk is a simple mobility model based on random directions and speeds.

In this mobility model, a mN moves from its current location to a new location by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from pre-defined ranges, [min_speed; max_speed] and [0;2p] respectively. Each movement in the Random Walk Mobility Model occurs in either a constant time interval t or a constant distance travelled d, at the end of which a new direction and speed are calculated. If a mN which moves according to this model reaches a simulation boundary, it “bounces” off the simulation border with an angle determined by the incoming direction. The mN then continues along this new path. Many derivatives of the Random Walk Mobility Model have been developed including the 1-D, 2-D, 3-D, and d-D walks [Camp 2002].

For supporting mobility of mobile agent in OMNeT++, Mobility framework is needed. With installing OMNeT++ Mobility Framework, it is able to make simulation for all scenarios which use mobile nodes. The core framework implements the support for node mobility, dynamic connection management and a wireless channel model. Additionally the core framework provides “basic modules” that can be derived in order to implement own modules. The mobility framework of OMNeT++ can be applied for simulating below networks [OMNeT++ 2008]:

- Fixed wireless networks
- Mobile wireless networks
- Distributed (ad-hoc) and centralized networks
- Sensor networks
- Multichannel wireless networks
- Many other simulations that need mobility support and / or a wireless interface.

Figure 4.14 shows Tkenv environment of OMNeT++ during execution of IANRA-MANET scenario.

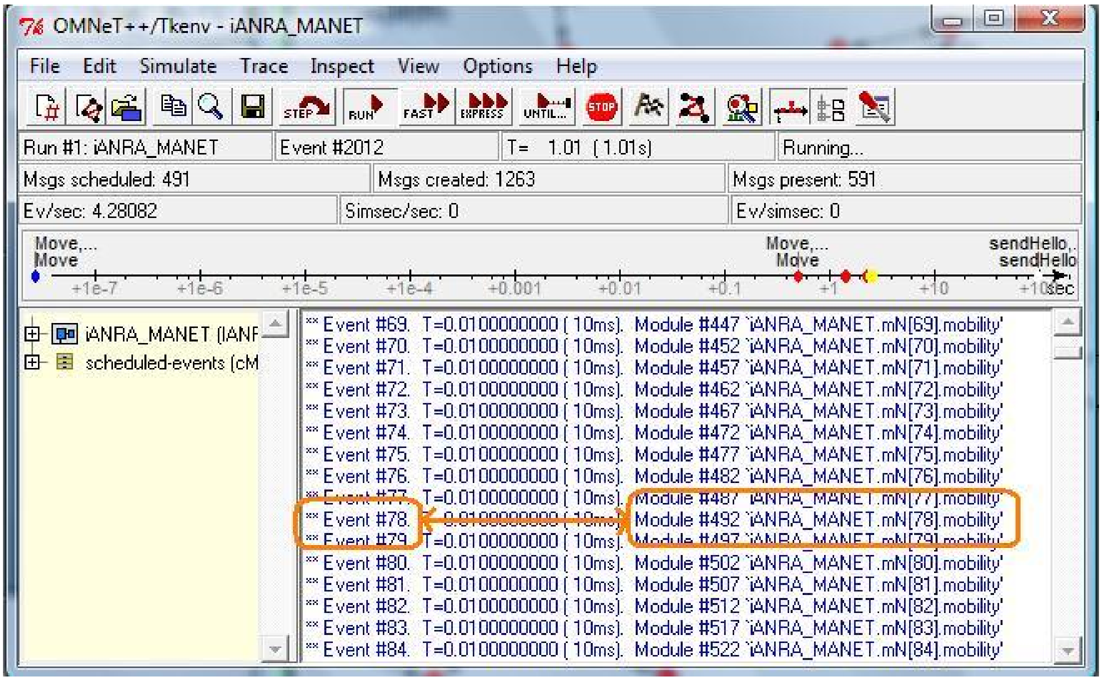


Figure 4.14. Mobility Events and Modules in IANRA Simulation

4.4.5 Network Protocol and Radio Communications Model

For radio communication models in both mesh and mobile ad hoc scenarios, IEEE 802.11b is used and bandwidth at the MAC layer is considered 2Mbit/s. For data generation from source node, Constant Bit Rate (CBR) is assumed in transport layer. According to the evaluation of IANRA for load balancing purpose, two high and low data rate (high and low load on the networks) are used in the source node. Also, to evaluate IANRA different number of mobile nodes is used in several simulations to evaluate selected metrics by increasing and decreasing number of mobile nodes on the networks as well as packet generation rate.

More details and assumption of simulation is given in the next chapter, like packet generation rate, packet size, mobile nodes speed, etc.

4.5 Summary

This chapter focused on methodology part of IANRA routing algorithm research. Following by overview of this chapter Intelligent AntNet based Routing Algorithm introduced. In IANRA routing algorithm all of the reactive Forward Ants is able to breeding and use their generation to forward to the next hop for discovery purpose. By using this method the generation are able to find shortest path and detect optimum and near-optimum paths between source and destination nodes.

To achieve all targets of IANRA, it is divided in three phases; path discovery, proactive route maintenance and handling for link failure. In the first phase, IANRA used reactive Forward Ant, its generations and Backward Ant to find optimum and near-optimum routes. In the second phase of IANRA, for maintaining the optimum and near-optimum routes, proposed algorithm applied proactive Forward Ants. An important role in this process is played by hello messages. In IANRA, nodes include in hello messages they send out routing information they have about active destinations. The third phase of IANRA is responsible to handle link failure in the network. For this reason proposed IANRA uses link failure notification message and at the same time this phase tries to solve and repair occurred problem by using rout repair ants.

In preparing to simulation section, the communication network models for proposed IANRA were discussed followed by brief description of OMNeT++ discrete event simulator system which is used for preparing IANRA scenarios. In this chapter two communication network models, mobile ad hoc and wireless mesh networks are discussed with their topologies for simulation. For mobility model of mobile nodes in the both mesh and ad hoc scenarios, Random Walk mobility model is used. For implementation of mobility in OMNeT++, its Mobility Framework (MF) installed to support mobility of the mobile nodes. For radio communication models in both mesh and mobile ad hoc scenarios, IEEE 802.11b is used and bandwidth at the MAC layer is considered 2Mbit/s.

The next chapter presents simulation results and discussion based on three main metrics; Average end-to-end packet delay, Packet delivery ratio and Packet overhead.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Overview

In previous chapter, the methodology used in IANRA routing algorithm was discussed in details. In this chapter, the results which were gathered after simulation via OMNeT++ software are presented and discussed. The results are collected for several loads (especially for high and low load) conditions to evaluate load balancing performance for proposed IANRA compared to exciting related algorithms.

5.2 OMNET++ Simulation Parameters

Simulation was done by OMNeT++ discrete event simulation software [OMNeT++ 2008]. At the starting time of simulations, all mobile nodes placed randomly in simulation area. Also all mobile nodes in both scenarios observe the random walk mobility model. The speed of mobile nodes in this area was considered between 0 and 15 (m/s) randomly and they choose direction by chance.

For data traffic in the networks all source nodes is generated Constant Bit Rate (CBR) packets and forward it to direction of destination through intermediate nodes. At the MAC layer the popular 802.11b Distributed Coordination Function (DCF) is used. Moreover data rate at the PHY layer assumed 2Mbit/s and radio range 300 meters.

5.2.1 Parameters for Mobile Ad hoc Network Scenario

To evaluate proposed IANRA behaviour by increasing the percentage of fixed node in the networks, we tried to run simulation with considering percentage of fixed nodes in the networks between 0% and 50%. All parameters for mobile ad hoc network scenario are shown in Table 5.1.

Table 5.1. Simulation parameters of mobile ad hoc network scenario

Mobile ad hoc network scenario	
Parameters	Value
Number of mobile nodes	100
Data traffic type	Constant Bit Rate (CBR)
Simulation area	1500×1000 m^2
Simulation time	1800 sec
Mobile node speed	0-15 (meter/s)
Mobility model	Random Walk Model
MAC protocol	IEEE 802.11b
Transport layer protocol	UDP
Data rate in PHY layer	2 (Mbit/s)
Radio range in PHY layer	300 meters
Packet generation rate	1, 5, 10, 15, 20 (packets/s)
Data packet size payload	256 bytes
Percentage of fixed nodes	0% - 50%
Threshold time for backward ants	1 sec
τ_{hello}	1 sec

5.2.2 Parameters for Wireless Mesh Network Scenario

All data traffic, speed of mobile nodes, mobility model, threshold time for BA and τ_{hello} considered same as MANET scenario. Maximum hops between a mobile node (mN) and mesh router is 3. $Max(N)_{hops}$ is a maximum number of hops between a mN and MR. So, the maximum number of intermediate nodes in this simulation is ($Max(N)_{hops}$ -1). Table 5.2 shows all the parameters for wireless mesh network scenario used to evaluate IANRA.

Table 5.2. Simulation parameters of wireless mesh networks scenario

Wireless Mesh network scenario	
Parameters	Value
Number of mobile nodes	100
Number of wireless mesh routers	10
Maximum hops between mN and MR	3 hops
Data traffic type	Constant Bit Rate (CBR)
Simulation area	3000×2000 m^2
Simulation time	1800 sec
Mobile node speed	0-15 (meter/s)
Mobility Model	Random Walk Model
MAC protocol	IEEE 802.11b
Transport layer protocol	UDP
Data rate in PHY layer	2 (Mbit/s)
Radio range in PHY layer	300 meters
Packet generation rate	1, 5, 10, 15 & 20 (packets/s)
Data packet size payload	256 bytes
Percentage of fixed nodes	0% - 50%
Threshold time for backward ants	1 sec
τ_{hello}	1 sec

5.3 Performance Evaluation

In this research IANRA routing algorithm evaluated in a several simulations tests on both MANET and WMNs networks. The major aims of performance evaluation are to collect and compare the results for; (i) average end-to-end packet delay, (ii) packet delivery ratio and (ii) packet overhead.

5.3.1 Model Validation

In search of model validation for AntHocNet, we relayed on the reported results published by Di Caro et al. (2008). To validate obtained simulated results for AntHocNet, the behaviour of the published one has been investigated by simulated results in this research. Figure 5.1 and 5.2 show the results of AntHocNet for MANET scenario by Di Caro et al. [DiCaro 2008]. At the lowest data rate, AntHocNet shows high delay and low packet delivery. This is because it needs to set up a route between source and destination prior to communication. When data packets are sent sporadically, previously constructed routes can hardly ever be reused, and a new route set up is needed almost every time.

The achieved simulated result in this study for AntHocNet has been showed in Figures 5.3 and 5.4. By increasing the packet generation frequency the average end-to-end packet delay also increased in both reported and simulated results. Although, in low packet generation (2, 5 and 10 packets/s), AntHocNet showed lower average end-to-end delay (Figures 5.1 and 5.3). On the other hand, by increasing the date rate, packet over head decreased in both reported and simulated AntHocNet results (Figures 5.2 and 5.4). It caused due to increasing number of data packet in the network however the control packet increasing smoothly. Since, the trend of average end-to-end packet delay and packet overhead are same in both AntHocNet and the simulated one, the results of AntHocNet algorithm is reliable.

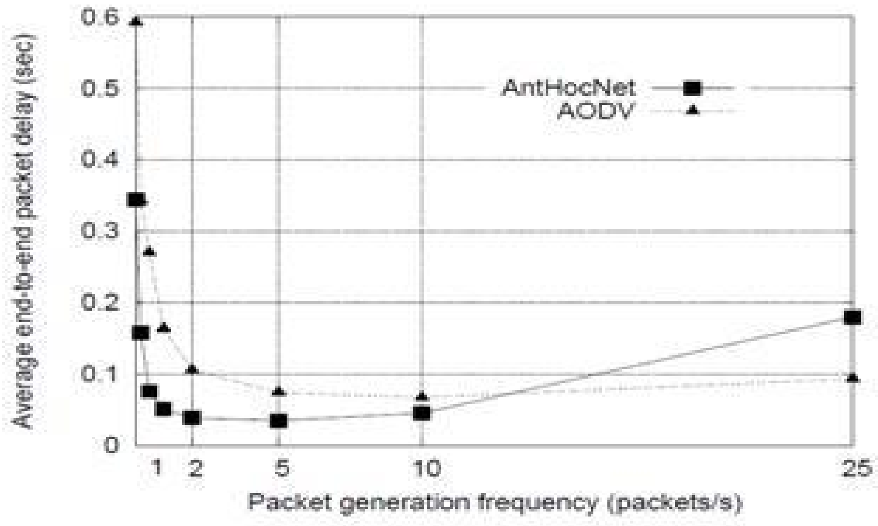


Figure 5.1. Average End-to-End Packet Delay versus Packet Generation Rate in AntHocNet Scenario [DiCaro 2008].

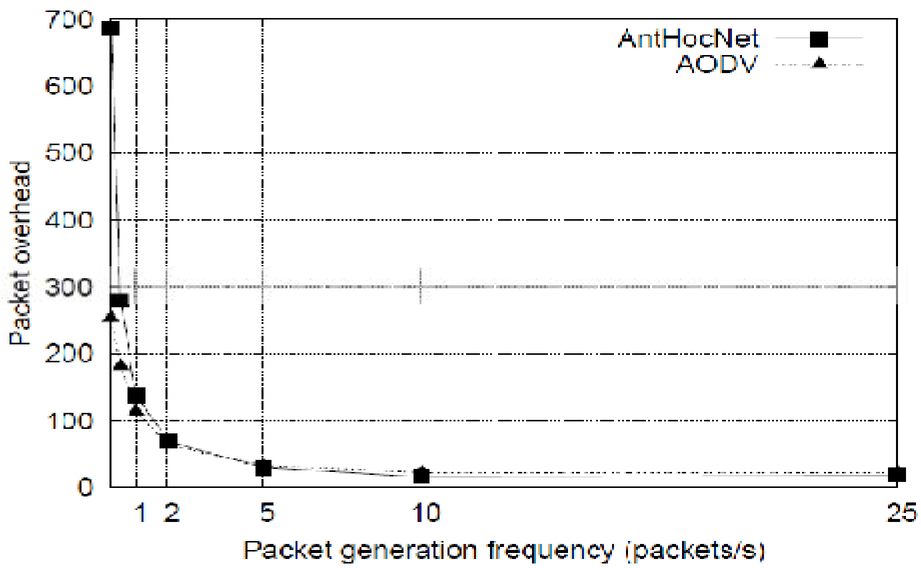


Figure 5.2. Packet Overhead versus Packet Generation Frequency in AntHocNet Scenario [DiCaro 2008].

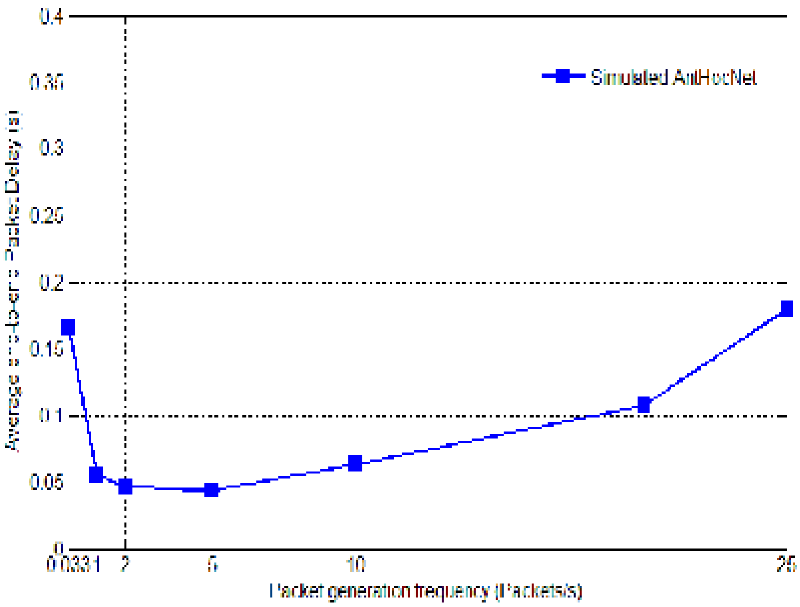


Figure 5.3. Average End-to-End Packet Delay versus Packet Generation Frequency in Simulated Algorithms for MANET Senario.

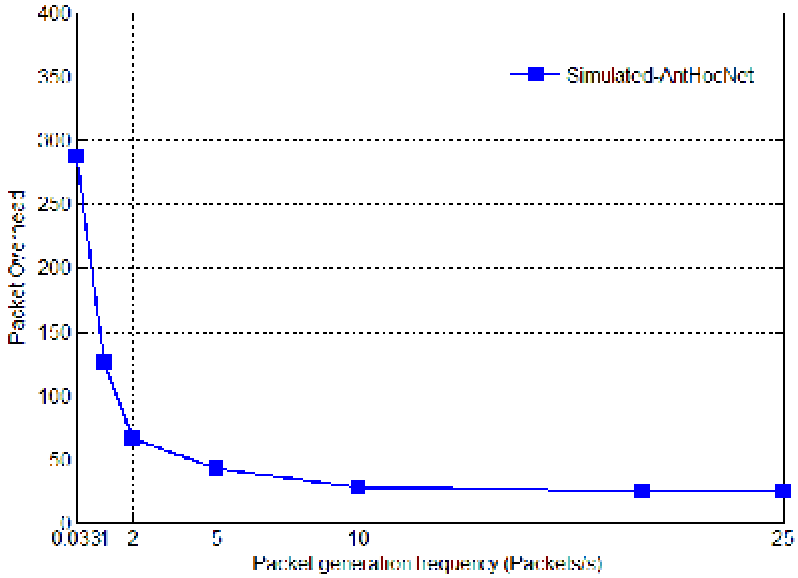


Figure 5.4. Packet Delivery Ratio versus Packet Generation Frequency in Simulated Algorithms for MANET Senario.

5.4 Average End-to-End Packet Delay

Three following Sub-sections, 5.4.1and 5.4.2, are given the results for Average end-to-end packet delay based on packet generation rate and percentage of fixed nodes in the networks respectively.

5.4.1 Average End-to-End Packet Delay versus Packet Generation Rate

Average end-to-end packet delay of MANET and WMNs scenarios is shown in Figures 5.5 and 5.6 respectively. In these graphs, the mentioned delay behaviour is compared by increasing packet generation frequency. For evaluation of proposed IANRA algorithm, low (1 packet/s), medium (4-15 Packets/s) and high (20 packets/s) load on the network are considered.

At the lowest packet generation frequency all of the algorithms show high delay. This is because all algorithms need to set up a route between source and destination. Also at the lowest data rate the results shows that packet over head is high because of setting up an optimum route. On the other hand, pheromone evaporation happens in lowest data generation rate which affects the optimum path formation. After vaporization of pheromone the source node must send FA to set up the optimum path again. Behaviour of average end-to-end packet delay between 5 and 15 limits is almost same for all of the algorithms. Because of increasing a packet generation rate, subsequent packets can profit from previous optimum route setups. By contrast, for high and medium packet generation rates an average end-to-end packet delay is increased approximately.

IANRA algorithm shows the lowest average end-to-end packet delay in comparison with the other algorithms in Figure 5.5. This is caused because of using several generations of forward ant (FA) for route discovery purpose and selecting sub-optimum routing paths in the network as well, in proposed IANRA routing algorithm. Figure 5.6 shows the same results for wireless mesh networks. Due to fixed wireless mesh routers in the WMN network the average end-to-end packet delay is decreased compared to MANET scenario. The basic role of mentioned routers is to forward data packets toward destination using the optimum and sub-optimum routes.

Average end-to-end packet delay is decreased 31.16%, 58.20% and 48.40% in MANET scenario, 52.86%, 64.52% and 62.86% by increasing packet generation rate in WMNs compared to AntHocNet, AODV and B-AntNet routing algorithms respectively.

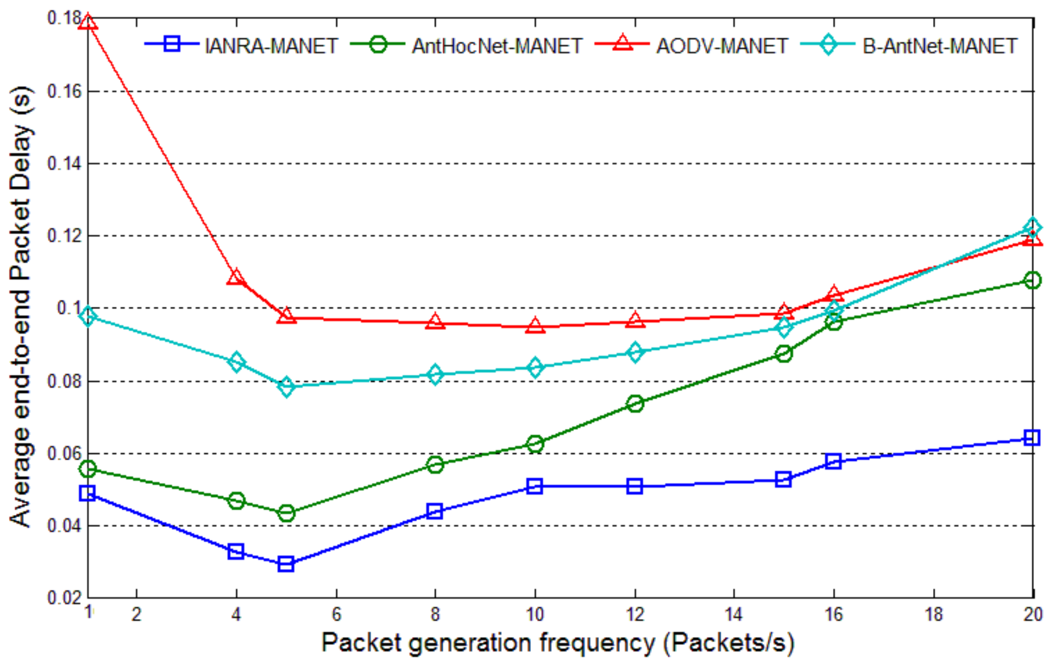


Figure 5.5. Average End-to-End Packet Delay versus Packet Generation Rate in MANET Scenario.

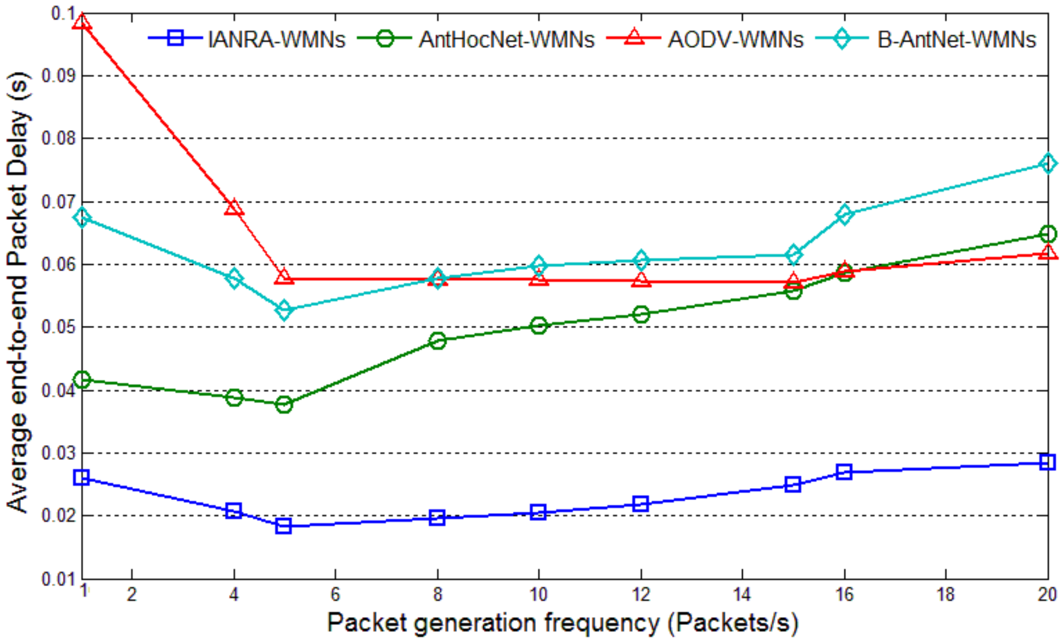


Figure 5.6. Average End-to-End Packet Delay versus Packet Generation Rate in WMNs Scenario.

Table 5.3 shows the reduction of percentage average end-to-end packet delay by IANRA for all considered packet generation frequency in MANET and WMN scenario compared AntHocNet, AODV and B-AntNet.

Table 5.3. Reducton of percentage of average end-to-end packet delay by IANRA by increasing packet generation rate

Packet Generation Rate	MANET Scenario			WMN Scenario		
	AntHocNet	AODV	B-AntNet	AntHocNet	AODV	B-AntNet
1(packet/s)	12.68165	72.69344	50.139495	37.79599	73.60923	61.51257
4 (packet/s)	30.26201	69.71867	61.646962	46.72283	69.95403	64.17644
5(packets/s)	32.46512	69.86524	62.448162	51.33913	68.28127	65.30775
8 (packet/s)	23.00741	54.23558	46.422771	58.91492	65.85571	66.05401
10(packets/s)	19.17311	46.48177	39.356158	59.50763	64.51556	65.93337
12 (packet/s)	30.86569	47.17429	42.034734	58.11721	62.04357	64.10895
15(packets/s)	39.75754	46.55436	44.30656	55.44013	56.5244	59.64348
18 (packet/s)	40.10959	44.27794	41.910465	54.09619	54.27054	60.40841
20(packets/s)	40.23012	45.89837	47.405924	56.06365	53.95675	62.55902

5.4.2 Average End-to-End Packet Delay versus Percentage of Fixed Nodes

By increasing the percentage of fixed nodes in the network, the observed results for simulation experiments of IANRA shows that the value of delay decrease. This occurred because of trying to set up the new optimum route according to the new place of the nodes. If the mobile nodes percentage increase then the optimum routes will be breaks in a short time and nodes loose the route then they need to start discovery for new optimum route in the networks.

Figures 5.7 and 5.8 show the behaviour of the average end-to-end packet delay of IANRA and three other algorithms in MANET and WMNs scenarios respectively. These figures show the effect of fixed nodes percentage in the networks with average end-to-end packet delay. They also show the effect of IANRA's route maintenance and handling link failure phases as average end-to-end packet delay is affected by a phases. Here, IANRA shows better results in comparison with AntHocNet, AODV and B-AntNet routing algorithms for both MANET and WMNs scenarios. Average end-to-end packet delay is decreased 55.60%, 65.77% and 66.65% in MANET scenario, 26.02%, 36.72% and 42.52% in WMN by increasing percentage of fixed nodes compared to AntHocNet, AODV and B-AntNet routing algorithms respectively.

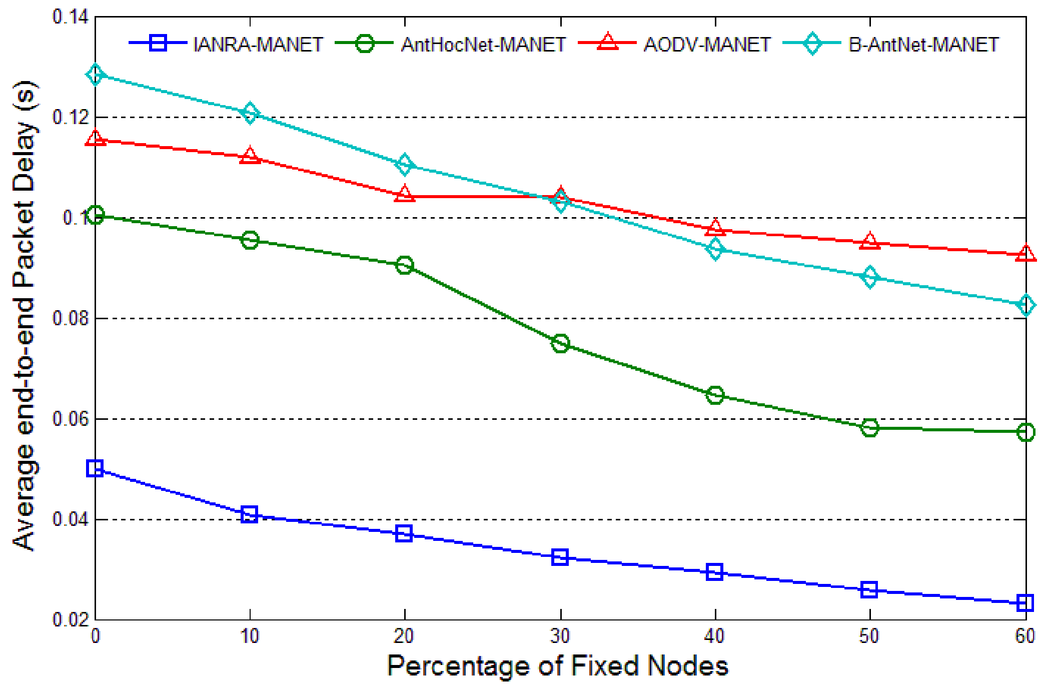


Figure 5.7. Average End-to-End Packet Delay versus Percentage of Fixed Nodes in MANET Scenario.

Table 5.4 depicted the decrease percentage of average end-to-end packet delay versus percentage of fixed nodes in the networks by IANRA routing algorithm rather than three compared algorithms in both mobile ad hoc and wireless mesh networks scenario.

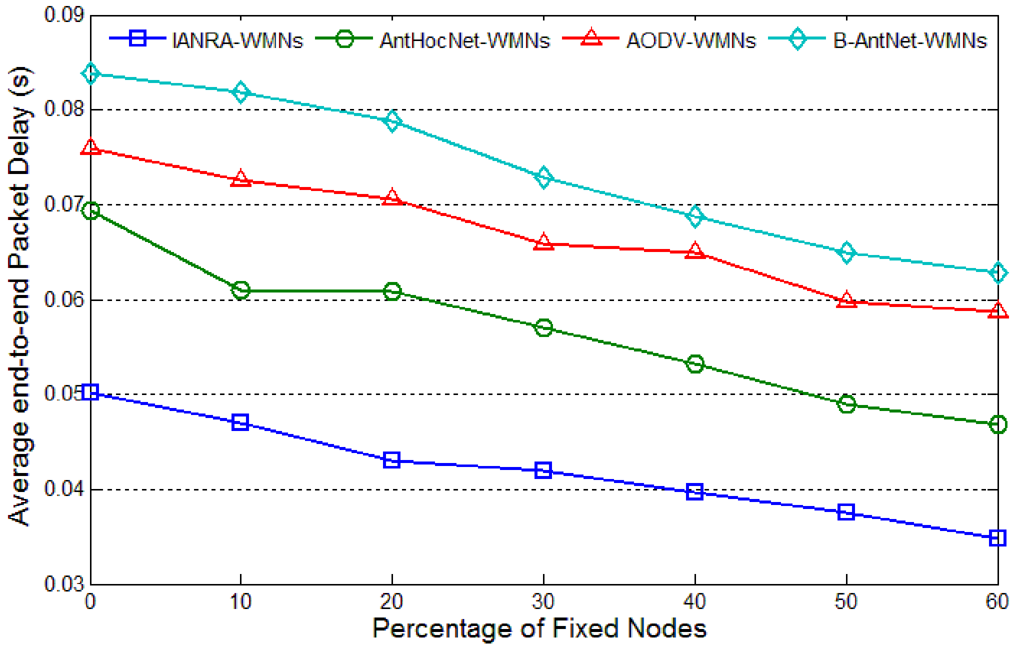


Figure 5.8. Average End-to-End Packet Delay versus Percentage of Fixed Nodes in WMNs Scenario.

Table 5.4. Reduction of percentage average end-to-end packet delay by IANRA by increasing percentage of fixed nodes.

% of fixed nodes	MANET Scenario			WMN Scenario		
	AntHocNet	AODV	B-AntNet	AntHocNet	AODV	B-AntNet
0%	50.3480	56.8001	61.1430	27.7296	34.0195	40.1949
10%	57.1824	63.4268	66.1707	22.9000	35.3134	42.6288
20%	59.1073	64.5228	66.4771	29.3343	39.0962	45.4300
30%	57.1686	69.1532	68.8649	26.6116	36.4035	42.5361
40%	54.6935	70.0174	68.8460	25.4295	38.7629	42.2261
50%	55.6344	72.7988	70.6708	23.3511	37.1918	42.1686
60%	59.66654	75.12099	72.09905	25.82992	40.72666	44.60908

5.5 Packet Delivery Ratio

The behaviour of packet delivery ratio is shown in Sub-sections 5.5.1 and 5.5.2 by increasing the packet generation frequency and number of nodes in the networks. In

Sub-sections 5.5.2 and 5.5.3 the results for packet delivery ratio are shown with increasing percentage of fixed nodes.

5.5.1 Packet Delivery Ratio versus Packet Generation Rate

By impose the high load in the network, we except that the packet delivery ratio decrease. This is because of congestion on the optimum route as well as congestion on queue in the nodes. The simulation results confirm above reasons. Figures 5.9 and 5.10 show the results of MANET and WMNs scenarios for packet delivery ratio by increasing the packet generation frequency respectively.

In IANRA and AntHocNet routing algorithms, where routes are proactively maintained and therefore remain valid for a longer duration. This effect is visible at the lowest packet generation rates compared to AODV and B-AntNet. In general we can see that IANRA's strategy is more effective in terms of packet delivery ratio. This happens because of using sub-optimum path in IANRA. Contrariwise, during the route maintenance, proactive FAs try to compensate the pheromone evaporation on the optimum path. These mentioned reasons minimise requirement of new route setup and more route repair attempt.

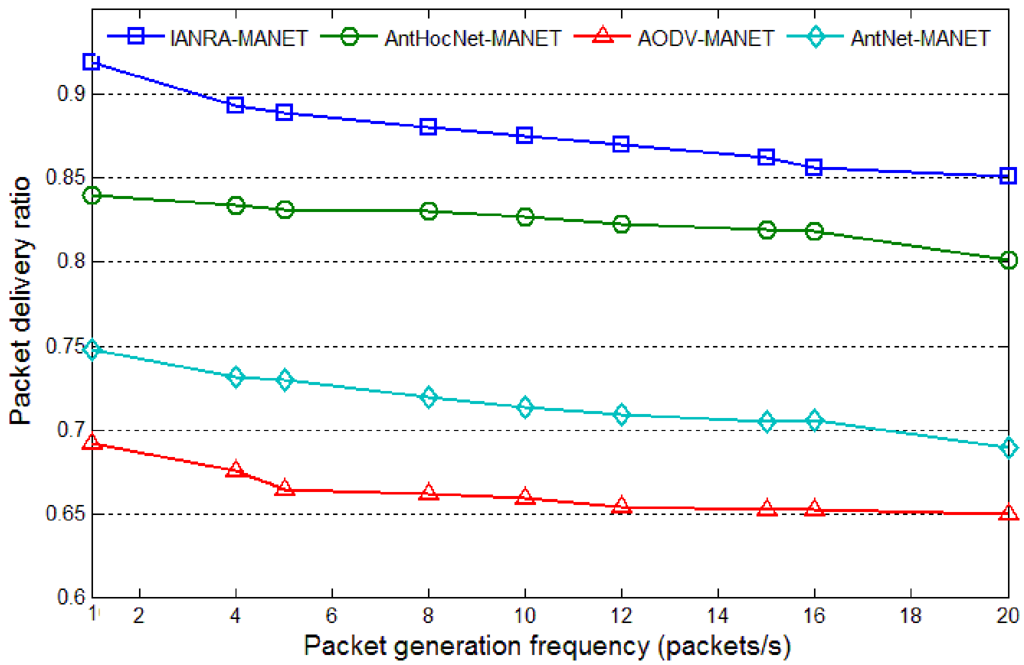


Figure 5.9. Packet Delivery Ratio versus Packet Generation Frequency in MANET Scenario

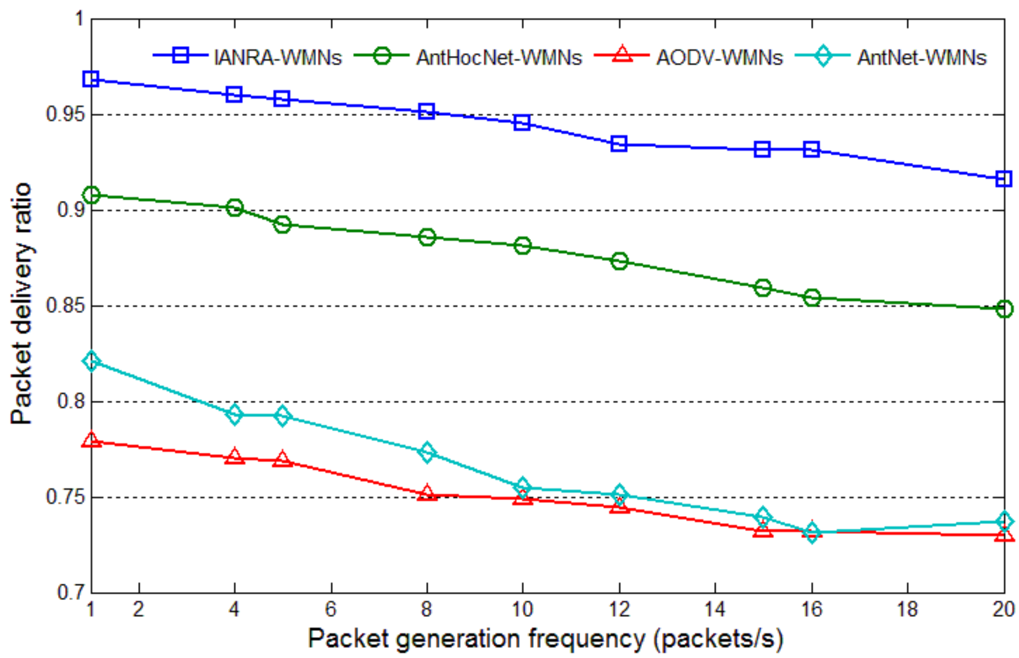


Figure 5.10 Packet Delivery Ratio versus Packet Generation Frequency in WMNs Scenario

Hence, in IANRA packet delivery ratio increase 6.31%, 24.47% and 18.39% in MANET scenario; 6.97%, 20.32% and 18.52% in WMN increasing packet generation frequency compared to AntHocNet, AODV and B-AntNet routing algorithms respectively. In other words, IANRA is capable to deliver 87.91% and 94.36% of the packets from source node to destination successfully in MANET and WMNs respectively.

5.5.2 Packet Delivery Ratio versus Number of Nodes

In the second part of the results for packet delivery ratio, effect of the number of nodes in the network evaluated. At the beginning of simulation experiment 25 mobile nodes were considered, followed by 50, 75, 100, 125, 150 and 175 mobile nodes in the networks. The same simulation execution was done for both low and high data load in the networks. One CBR (packet/s) and 20CBR (packets/s) assumed in order to low and high data load in the networks respectively.

Figures 5.11 and 5.12 depict the results for packet delivery ratio for 1CBR and 20 CBR packets per second in MANET scenario. It is visible that the performance of proposed IANRA is better than three others in both MANET and WMNs. This happened because of better output of route maintenance and handling the link failure phases in proposed IANRA routing algorithm. Furthermore selecting one sub-optimum route in both scenarios is helping IANRA to give finer performance in comparison with other three algorithms.

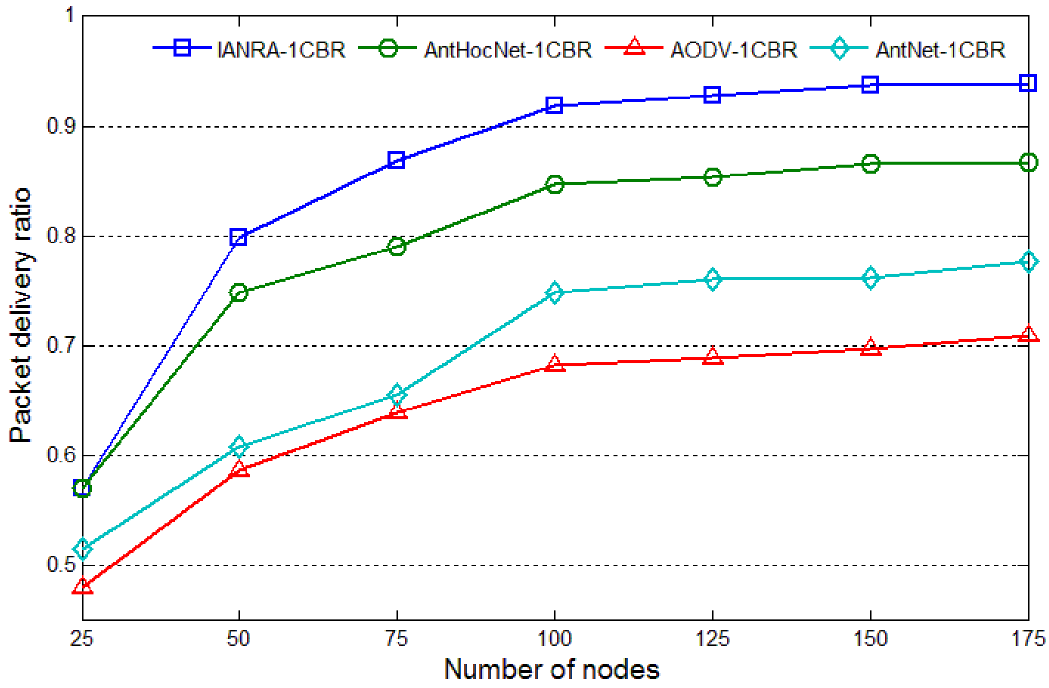


Figure 5.11. Packet Delivery Ratio versus Number of Nodes in MANET Scenario With 1(packet/s) CBR Packet Generation Rate.

By changing the packet generation rates to 20CBR (Packets/s) in MANET, performance of IANRA and three other algorithms decrease noticeable as shown in Figure 5.8. When packet generation from source node change to 20 packets per second, the number of data packets toward destination increase by lapse of time on the optimum path and incoming queue of intermediate nodes. Therefore, average end-to-end packet delay increase in the network as time passes. This behaviour in the network cause packet delivery ratio to reduce in the network. The difference of the packet delivery ratio range in Figures 5.11 and 5.12 demonstrate above reasons manifestly.

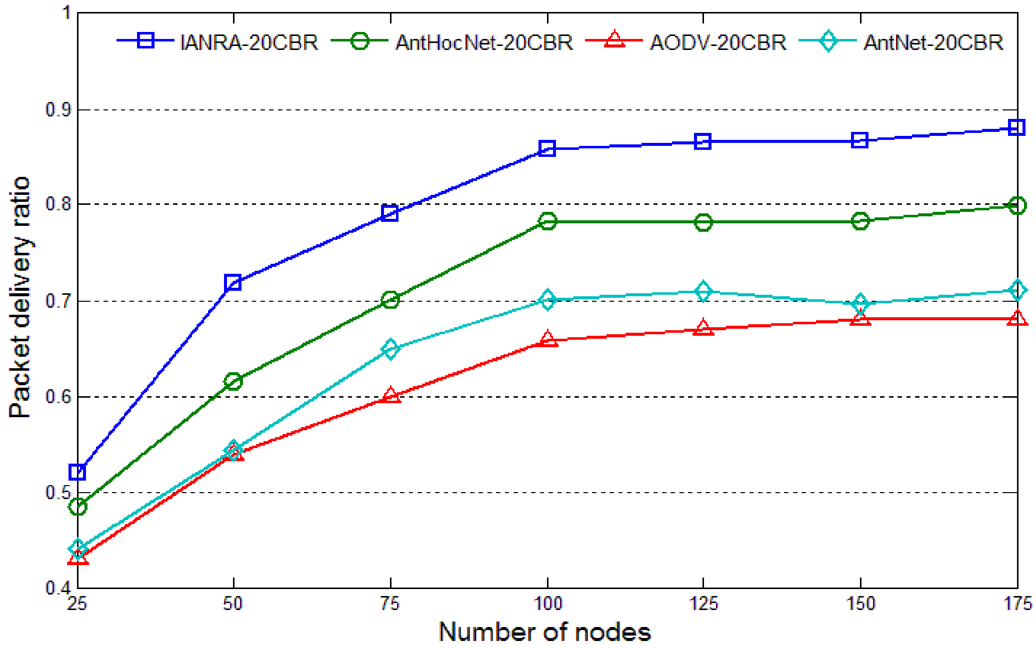


Figure 5.12. Packet Delivery Ratio versus Number of Nodes in MANET Scenario With 20 (packets/s) CBR Packet Generation Rates.

The same packet delivery ratio results for IANRA-WMN algorithms are shown in Figures 5.13 and 5.14 for one and 20 packets/s respectively.

According to the Figures 5.7 to 5.10, the packet delivery ratio for WMNs is slightly higher than MANET scenario as expected. This happens because in WMNs networks there is especial devise (MR) for routing purpose unlike MANET. For that reason WMNs scenario gives higher performance than MANET scenario in order to packet delivery ratio.

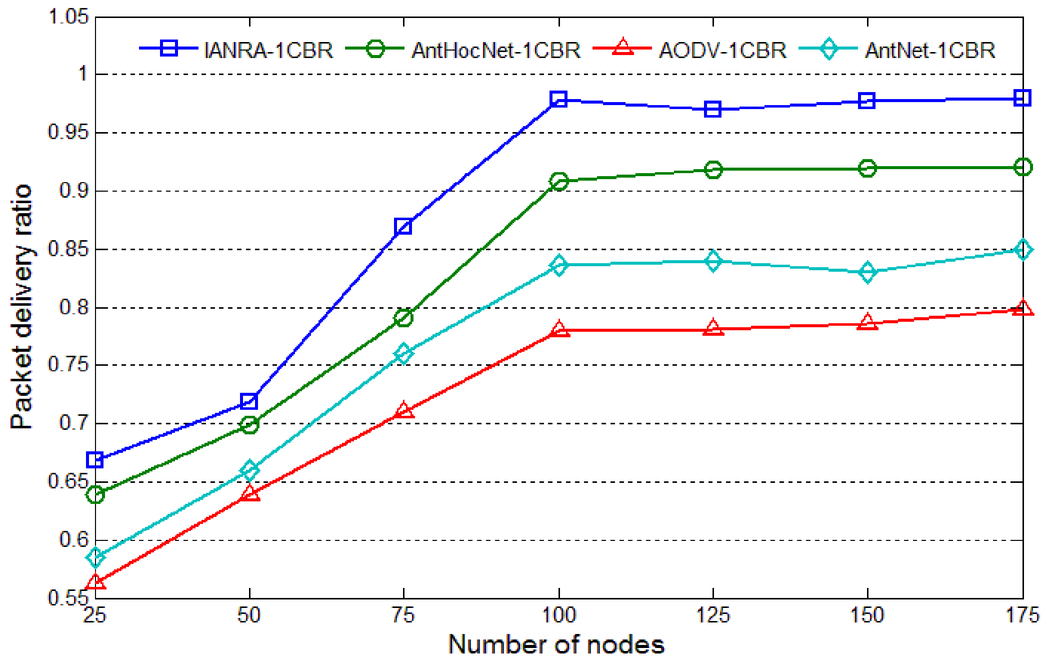


Figure 5.13. Packet Delivery Ratio versus Number of Nodes in WMNs Scenario With 1(packet/s) CBR Packet Generation Rates.

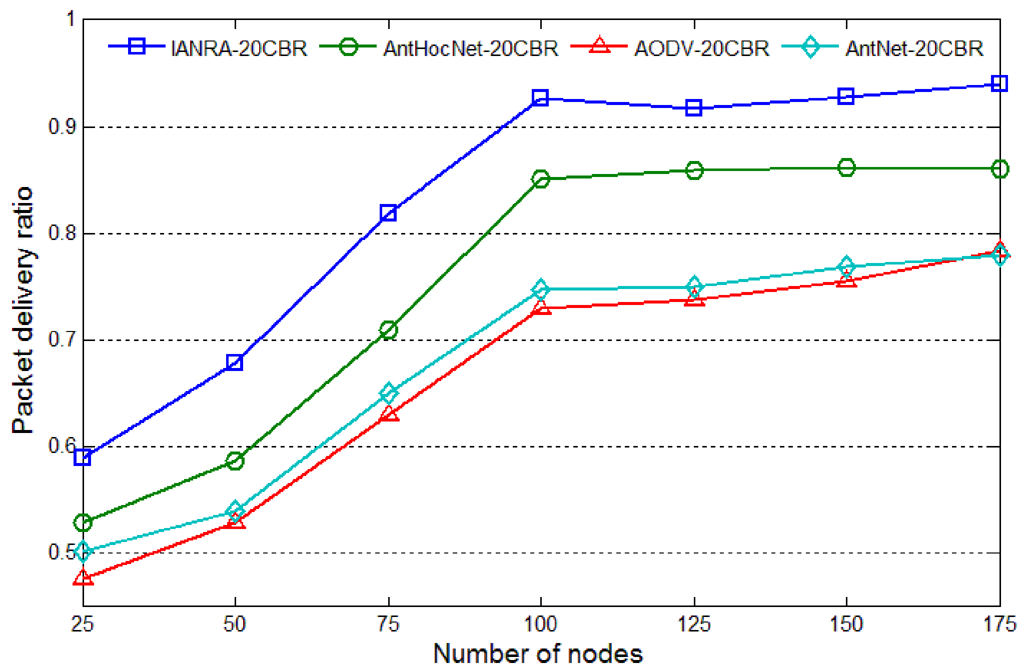


Figure 5.14. Packet Delivery Ratio versus Number of Nodes in WMNs Scenario With 20 (packets/s) CBR Packet Generation Rates.

Table 5.5 shows percentage of improvement by IANRA routing algorithm for both mobile ad hoc network and wireless mesh scenarios in order to packet delivery ratio by increasing the number of the mobile nodes in the networks. The table depicts the improvement percentage for low and high data load on the networks with one and 20 packets per second.

Table 5.5. Percentage of improvement by IANRA for packet delivery ratio rather than three compared algorithms

Compared Algorithms	MANET scenario		WMNs scenario	
	1 packet/s	20 packets/s	1 packet/s	20 packets/s
AntHocNet	6.3434	10.4894	6.0821	11.1764
AODV	24.3086	22.9014	16.7997	21.5070
B-AntNet	19.9332	19.1554	12.1509	19.0469

5.5.3 Packet Delivery Ratio versus Percentage of Fixed Nodes

Number of mobile nodes and their speed in the network are the main factors which affect the packet delivery ratio. It is expected that all of the generated packets by source nodes need to follow optimum route toward destination. When some of the mobile nodes which are member of optimum route move to different place and out of previous coverage area, the optimum route will be broken and the nodes need to setup new route to send data packets toward destination.

According to the above mentioned reasons, proposed IANRA algorithm is evaluated in order to packet delivery ratio by increasing percentage of fixed nodes in both

MANET and WMNs. Furthermore, in simulation experiment low (1 packets/s) and high (20 packets/s) data load on the networks considered.

Figures 5.15 and 5.16 depicts packet delivery ratio versus percentage of fixed nodes on the MANET network with low (1 CBR packet/s) and high (20 CBR packets/s) data rate respectively. The observed results of IANRA simulation shows that proposed algorithm increased packet delivery ratio 7.08%, 26.02 % and 23.81% with one CBR (packet/s) data rate (Figure 5.15) and 6.16%,20.61% and 19.47% with 20 CBR (packets/s) (Figure 5.16) in comparison with AntHocNet, AODV and B-AntNet respectively.

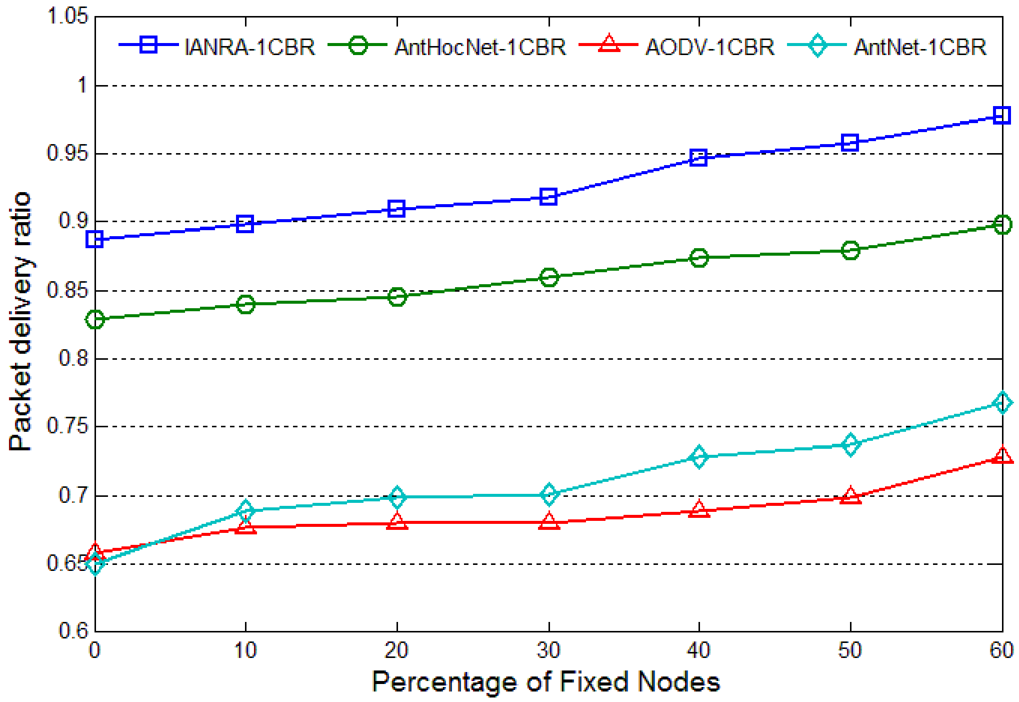


Figure 5.15. Packet Delivery Ratio versus Percentage of Fixed Nodes in MANET Scenario With 1(packet/s) CBR Packet Generation Rate

In wireless mesh networks, most of the mobile Nodes (mN) in the network connect to the mesh router directly, therefore, the rest of routing process done by the MR too and the mobile nodes have no intervene in this stage. Here, the main part of the optimum route is formed by the direct connection links among MR.

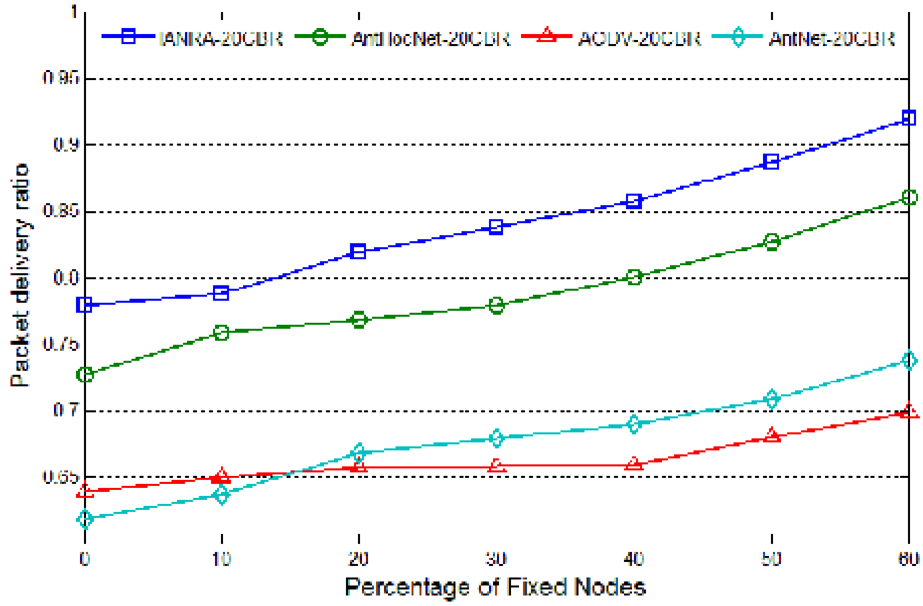


Figure 5.16. Packet Delivery Ratio versus Percentage of Fixed Nodes in MANET Scenario With 20 (packet/s) CBR Packet Generation Rates

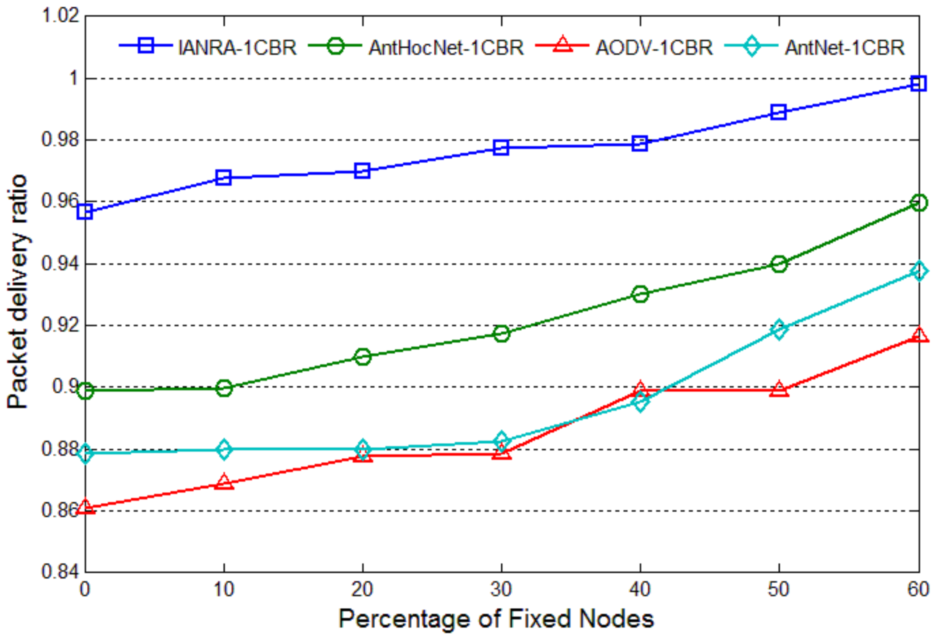


Figure 5.17. Packet Delivery Ratio versus Percentage of Fixed Nodes in WMNs Scenario With 1(packet/s) CBR Packet Generation Rates

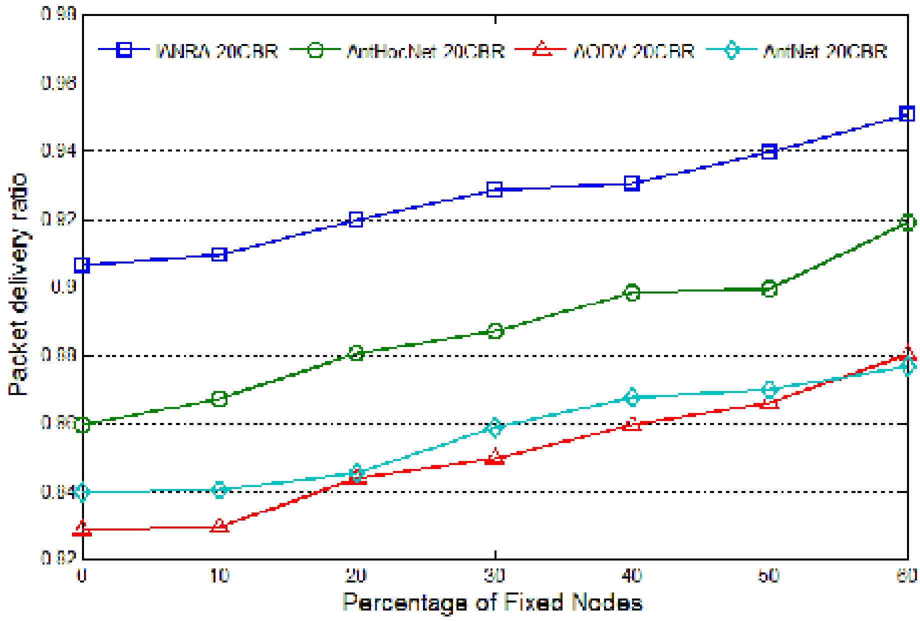


Figure 5.18. Packet Delivery Ratio versus Percentage of Fixed Nodes in WMNs Scenario With 20 (packets/s) CBR Packet Generation Rates

The IANRA-WMNs increased packet delivery ratio 5.86%, 9.50 % and 8.63% with one CBR packet/s (Figure 5.17) and 4.35%, 8.24% and 7.45% with 20 CBR packets/s (Figure 5.18), in compared to AntHocNet, AODV and B-AntNet respectively. Table 5.6 depicted the average of packet delivery percentage in order to percentage of fixed nodes between 0% and 50% on both mobile ad hoc and mesh networks for low and high data load on the network.

Table 5.6. Average percentage of packet delivery ratio between 0% and 60% of fixed nodes.

	MANET		WMNs	
	1 CBR (p/s)	20 CBR (p/s)	1 CBR (p/s)	20 CBR (p/s)
IANRA	91.96915	82.77898	97.31571	92.25642
AntHocNet	85.45564	77.67529	91.60842	88.23414
AODV	68.03115	65.72566	88.06487	84.65325
B-Antet	70.07749	66.65589	88.91702	85.38854

5.6 Packet Overhead

In IANRA routing algorithm proactive forward ants (small packets) are used as control packets to maintain the optimum and sub-optimum route in the network. Multiplicity of control packets in the networks is one of the factors which create congestion in the network. For the reason that control packet is important in entire routing algorithms, IANRA algorithm evaluated in terms of packet overhead in number of control packets per received data packet.

Here the effected of packet overhead are shown in terms of packet generation rate and percentage of fixed node in sub-sections 5.6.1 and 5.6.2 respectively.

5.6.1 Packet Overhead versus Packet Generation Rate

Packet overhead in the network is affected by packet generation rate by source node. Figure 5.19 shows high amount of packet overhead for lowest packet generation rate, and gradually reduced with the increased packet generation rate. In the low data rate (1 and 5 packets/s) the packet overhead is high because all the nodes try to setup route for data communication while pheromone evaporation on the paths is fast. Therefore, concentration of the pheromone on a selected route is extremely low. In this condition, for discovering the route and after that for maintenance the selected route more control packets are sent in the network. Same thing happen for AODV algorithms when it is going to send hello message for the neighbours and RREQ message.

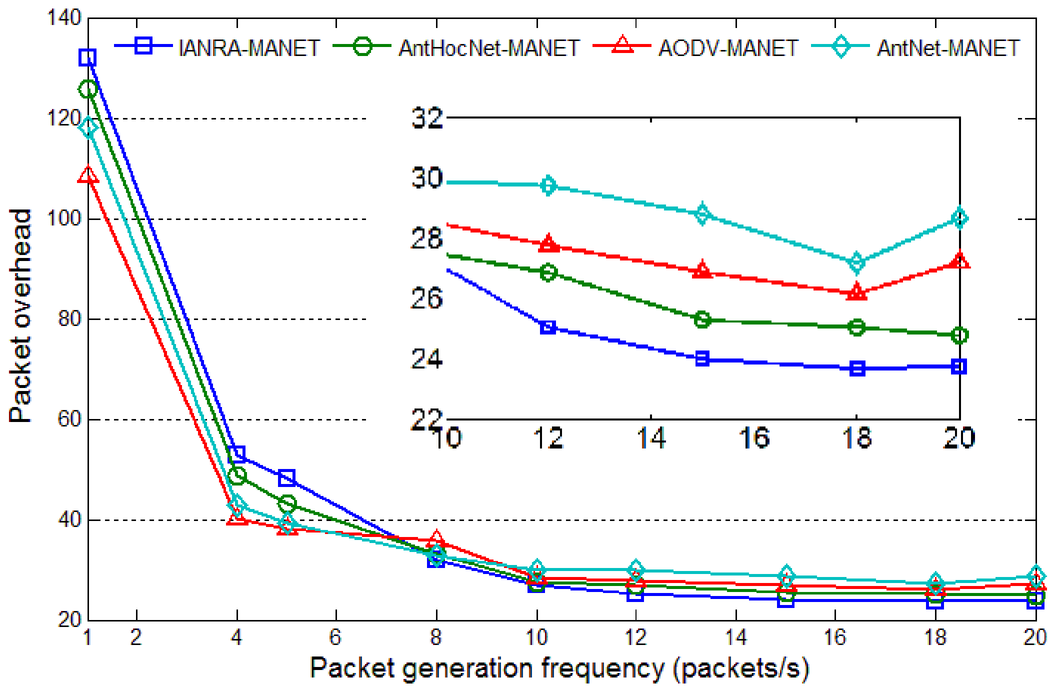


Figure 5.19. Packet Overhead verses Packet Generation Frequency in MANET Scenario.

In both Figures 5.19 and 5.20, IANRA gives slightly higher packet overhead for low data rate but for higher packet generation rates (10, 15 and 20 packets/s) packet overhead value decrease smoothly and it shows lowest packet overhead in comparison with other three compared algorithms (Table 5.7).

Packet overhead in wireless mesh network scenario is significantly lower than mobile ad hoc scenario in order to packet generation rates due to existence of mesh routers in the mesh networks. Table 5.7 shows percentage of IANRA's packet overhead value in order to packet generation frequency in contrast with three compared algorithms. In the mentioned table '-' denoted to decrease percentage of IANRA's packet overhead rather than others and vice versa.

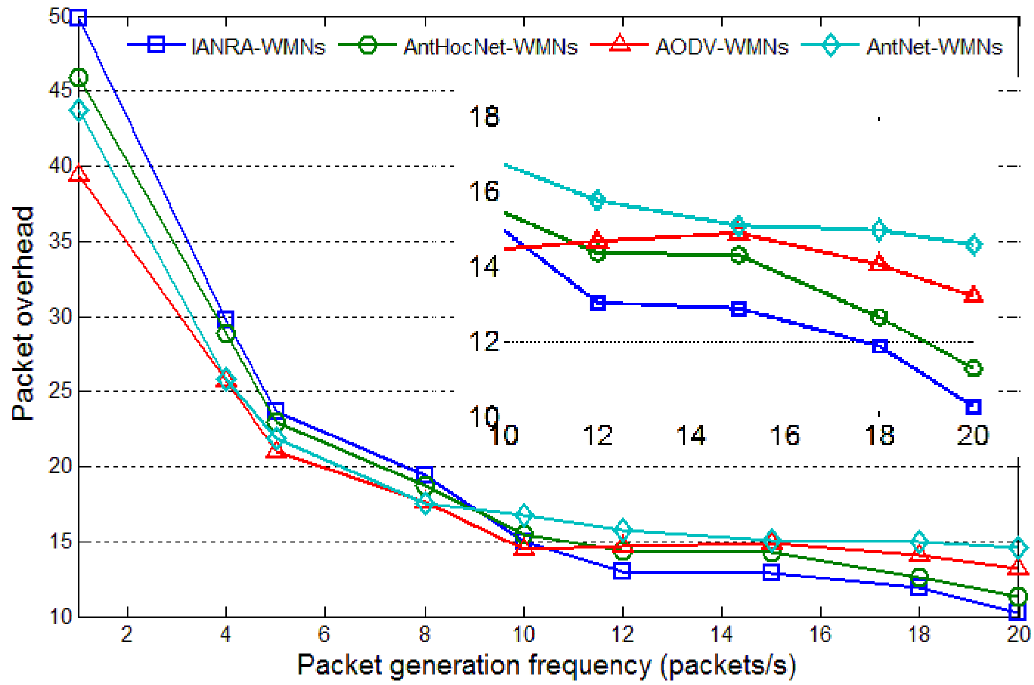


Figure 5.20. Packet Overhead verses Packet Generation Frequency in WMNs Scenario.

Table 5.7. Percentage of IANRA's packet overhead in order to data rate in contrast with three compared algorithms.

Packet generation rate	MANET scenario			WMNs scenario		
	AntHocNet	AODV	B-AntNet	AntHocNet	AODV	B-AntNet
1 p/s	4.5520	17.7772	10.5372	8.0256	20.9383	12.2626
4 p/s	7.774575	24.29108	19.292044	2.986363	13.44451	13.13939
5 p/s	10.4184	20.8781	18.1638	2.6020	11.1573	7.3481
8 p/s	-4.123053	-12.5927	-2.798651	3.45688	9.167756	9.6308
10 p/s	-1.7540	-5.4660	-10.7062	-3.1588	3.5045	-11.6923
12 p/s	-7.316216	-10.8651	-18.85093	-10.1203	-12.6737	-20.9339
15 p/s	-1.6433	-8.0284	-15.6696	-10.9316	-15.5029	-17.1444
18 p/s	-5.787088	-10.4799	-14.79427	-6.54868	-18.3591	-26.1066
20 p/s	-4.3886	-14.5401	-20.8101	-9.9686	-28.5815	-42.0062

5.6.2 Packet Overhead versus Percentage of Fixed Nodes

It is quite manifest that with increasing mobility in the networks packet overhead is increase in the networks. Figures 5. 21 and 5.22 confirm this matter for MANET and WMNs scenarios respectively. In both graphs with increasing percentage of fixed nodes in the network packet overhead is reduced smoothly for 20 packets/s packet generation rate.

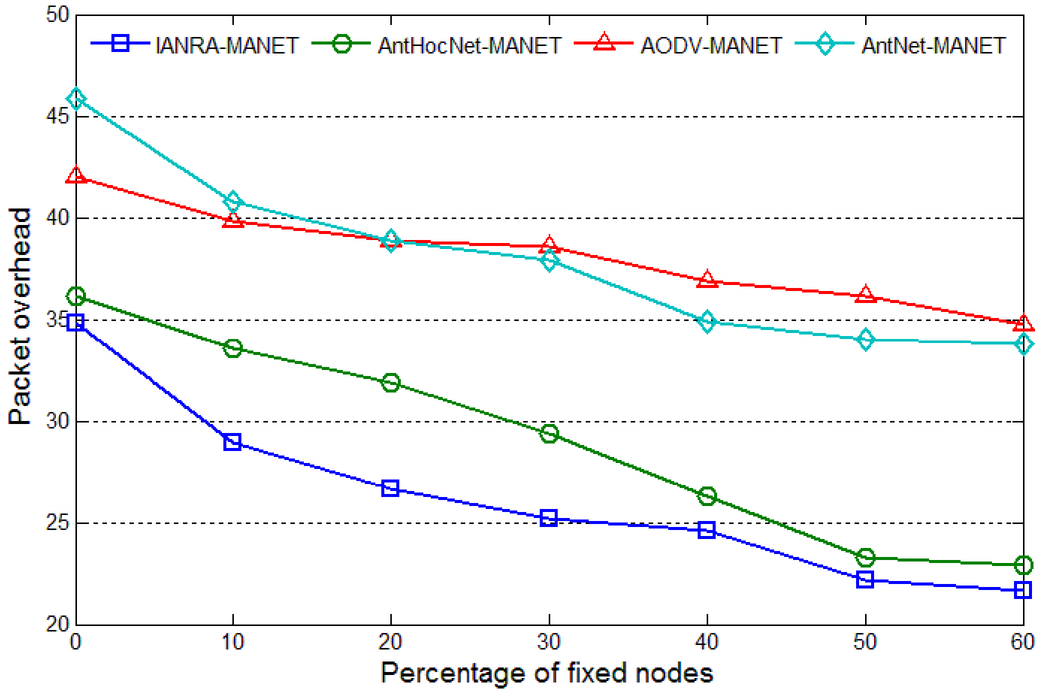


Figure 5.21. Packet Overhead verses Percentage of Fixed Nodes in MANET Scenario.

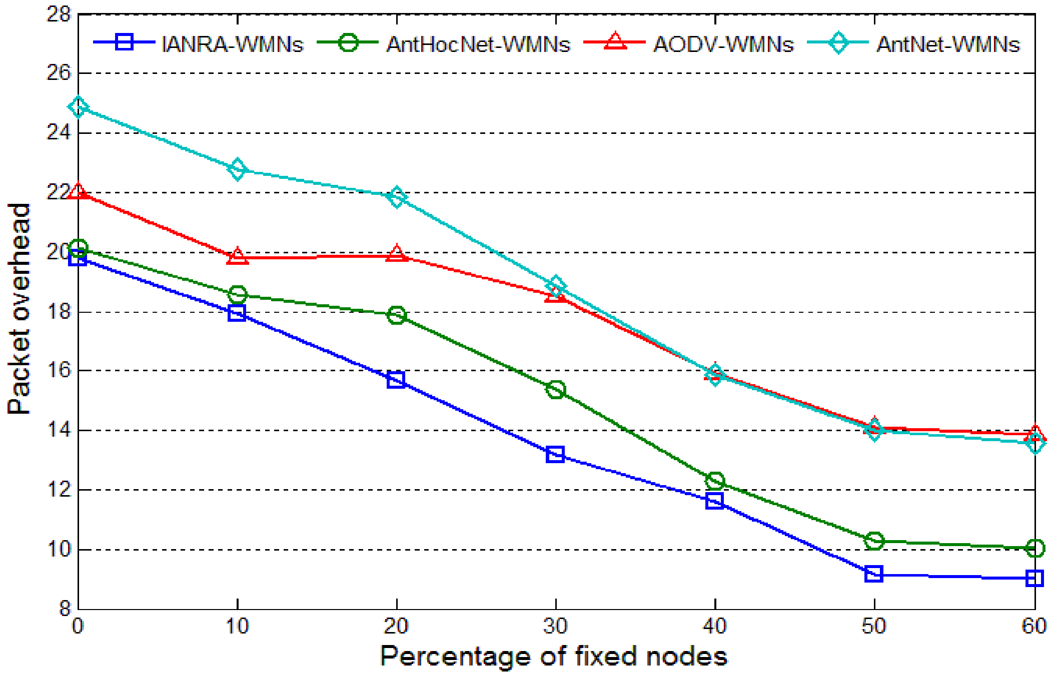


Figure 5.22. Packet Overhead verses Percentage of Fixed Nodes in WMNs Scenario

Table 5.8 shows percentage of IANRA's packet overhead by increasing percentage of fixed nodes in the networks in contrast with three compared algorithms. Same as Table 5.7, in this table '-' denoted to decrease percentage of IANRA's packet overhead rather than others.

Table 5.8. Percentage of IANRA's packet overhead in order to percentage of fixed nodes in contrast with three compared algorithms.

		MANET scenario			WMNs scenario		
		AntHocNet	AODV	B-AntNet	AntHocNet	AODV	B-AntNet
Percentage of fixed nodes	0%	-3.7427	-17.1789	-8.4377	-1.7507	-10.0693	-20.4484
	10%	-13.7483	-27.2754	-2.3947	-3.2747	-9.3620	-21.2114
	20%	-16.4133	-31.4588	0.1465	-12.4893	-21.2911	-28.2945
	30%	-14.3609	-34.6714	1.7488	-14.4292	-28.9228	-30.1940
	40%	-6.4312	-33.3563	5.7808	-5.6197	-27.0944	-27.0204
	50%	-4.8040	-38.6050	6.1935	-10.8746	-35.0123	-34.5206

	60%	-5.3473	-37.7195	2.9613	-9.7971	-34.7471	-33.4305

CHAPTER 6

CONCLUSION

6.1 Conclusion

In this research IANRA algorithm has been introduced based on Ant Colonies Optimization (ACO). IANRA is designed based on three phases: path discovery, route maintenance and handling for link failure. It uses multi generation of FA instead of only one type of FA. Furthermore, in IANRA algorithm sub-optimum route is discovered by forward ants as well as optimum route. For maintain these routes, it uses proactive forward ants. Therefore, IANRA is a hybrid routing algorithm.

Performances of IANRA, AntHocNet, AODV and B-AntNet have been investigated as well. IANRA evaluated in terms of three metrics which are average end-to-end packet delay, packet delivery ratio and packet overhead. In the all experiment, behaviour of IANRA evaluated with increasing packet generation rate, percentage of fixed nodes and number of nodes in the networks. IANRA shows better performance in terms of average end-to-end packet delay and packet delivery ratio for both mobile ad hoc and wireless mesh network scenarios. However the packet overhead of proposed algorithm is slightly higher than others in low data rate.

Finally, two current problems in ant colony's based algorithms which are (*i*) routing table freezes due to selecting same path and (*ii*) choosing a non-optimized route, have been eliminated.

6.2 Thesis Contributions

In this thesis, a novel routing algorithm (IANRA) has been proposed based on several generations of forward ants. One of the most important factors in IANRA is an ability of find near-optimum route as well as optimum route. By this procedure, IANRA can prevent route blocking in the network. This characteristic of IANRA affects performance of selected metrics such as average end-to-end packet delay and packet delivery ratio because the source node has option to select the possible paths to destination instead of only one optimum path in the network. Hence, the key achievements are as follows:

- IANRA routing algorithm: this algorithm designed based on FAs and their generation for path discovery purpose. Using few generations of FA and their breeding ability, route freezing problem has been solved with shortest path discovery in the network. When the data load increasing on a certain paths as an optimum path, the source node tries to forward the data packet via near-optimum paths. This mechanism prevents path blocking and route freezing in the network.

- Enhanced routing performance in terms of average end-to-end packet delay, packet deliver ratio and packet overhead in MANET and WMNs: the obtained results indicated that proposed IANRA's performance in the mentioned metrics is higher than AntHocNet, AODV and B-AntNet routing algorithms.

- Stabilized packet routing behaviour under several imposed data load in the networks: for both MANET and WMNs IANRA was evaluated for low, medium and high load (packet generation frequency) conditions. For all cases, IANRA shows better performance in comparison with the other selected available algorithms.

6.3 Future Research Direction

In future work, more complex metrics as pheromone, agent generation and new ability of ant based agent generations for enhance intelligent characteristics are planned to use. In application parts it seems that one of potential application for this algorithm is 6LoWPAN network to manage the energy efficient based routing between all FFDs and IPv6 gateway in IEEE802.15.4. Therefore, it is needed to investigate in details by creating its own scenario.

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APPENDICES

OMNETPP.INI CONFIGURATION FILE FOR IANRA SCENARIO

```
#omnetpp.ini

[General]
network = IANRA
ini-warnings = no
snapshot-file = snapShot.sna
output-vector-file = xputVect.vec
output-scalar-file = yputVect.sca
sim-time-limit = 30m
cpu-time-limit = 30m
total-stack-kb = 32768
num-rngs=5

[Cmdenv]
module-messages =no
event-banners =no
runs-to-execute = 1
express-mode = yes
status-frequency= 500000
default-run = 1

[Tkenv]
default-run= 1
slavelog = yes
slavelog-file = slave.log
use-mainwindow = yes
modmsgs-to-console = yes
animation-speed = 2.0
[Parameters]
#IANRA module
IANRA.height = 1500
IANRA.width = 1000
```

```
IANRA.dim = 100
#mobility model
;include Ini/avrSpeed.ini
;IANRA.MobileNode[*].mobilityModel = "RandomWalk"
;include Ini/randWalk.ini
IANRA.MobileNode[*].mobilityModel = "RestrictedRandWalk"
include Ini/resRWalk.ini
IANRA.MobileNode[*].mobilityModel = "RandomWP"
include Ini/randWP.ini
IANRA.MobileNode[*].mobilityModel = "RandomDirection"
include Ini/rDir.ini
IANRA.MobileNode[*].mobilityModel = "Pursuit"
include Ini/pursuit.ini
IANRA.MobileNode[*].mobilityModel = "Normal"
include Ini/normal.ini
#mobile host module
IANRA.MobileNode[*].x = intuniform(5,195)
IANRA.MobileNode[*].y = intuniform(5,195)
IANRA.MobileNode[*].routeAlgorithm = "IANRA_Adhoc"
IANRA.MobileNode[*].macAlgorithm = "SimpleMac"
#pyisic module
IANRA.MobileNode[*].physic.txPower =  uniform(9000,9900)
IANRA.MobileNode[*].physic.rxThreshold =  1
IANRA.MobileNode[*].physic.channelDelay = 0.0001
IANRA.MobileNode[*].physic.channelDatarate = 11.04858e+6
IANRA.MobileNode[*].physic.channelError = 0.000001
#mac module
IANRA.MobileNode[*].mac.promisqueMode = true;
IANRA.MobileNode[*].mac.inBufferSize = 8.38864e6
#application module
;pakets per secod
IANRA.MobileNode[*].app.rate = 3
;pakets of 512 byte = 2048 bit
IANRA.MobileNode[*].app.pktSize = 2048
;time elapsed  between two data burst
IANRA.MobileNode[*].app.burstInterval                    =
truncnormal(2,1.0)
```

```
;indicate the active hosts, they will generate traffic in
all the
;simulator run.
;Due to the different random position of each node
;fixing the host name that will work will not cause any
;statistical problem
IANRA.MobileNode[1].app.active = 1
IANRA.MobileNode[3].app.active = 1
IANRA.MobileNode[7].app.active = 1
IANRA.MobileNode[*].app.active = 0
```

BIODATA OF STUDENT

The author was born on 3rd of July, 1980 in SALMAS (West Azerbaijan), Iran. He received his Bachelor of Engineering degree in Hardware of Computer Engineering in 2006 from IAU University, Iran.

Currently, the author is undergoing his M.Sc. Program in Communications Network Engineering at Universiti Putra Malaysia (UPM), Malaysia. He is undertaking his research on swarm intelligence based routing algorithm for QoS based load balancing purpose in WMNs and MANET.

LIST OF PUBLICATIONS

The contents of this thesis have been published in the following journal and proceedings of the international conferences;

1. **Ayyoub A. Moghanjoughi**, Sabira Khatun, Borhanuddin B. M. Ali, Raja S. A. R. Abdullah, "Performance analysis of Ant Colony's algorithm: Load-balancing in QoS-based for wireless mesh networks routing", *International Review on Computer and* Software (IRECOS) Journal, ISSN 1828-6003, Vol. 3, N. 2, pp. 203-210, March 2008.

2. **Ayyoub A. Moghanjoughi**, Sabira Khatun, Borhanuddin B. M. Ali, Raja S. A. R. Abdullah, "An efficient Ant Colonies algorithm: QoS-Based load balancing for routing in Wireless Mesh Networks (WMNs)", *Proceeding of the International fifth IASTED AsiaCSN2008*, April 02-04, Langkawi, Malaysia, 2008, Published by ACTA Press, ISBN: 978-0-88986-734-5, pp. 90-97.

3. **Ayyoub A. Moghanjoughi**, Sabira Khatun, Borhanuddin B. M. Ali, Raja S. A. R. Abdullah, "Improving Ant Colony's Algorithm for QoS Based load balancing on Wireless Mesh Networks", *Proceeding of the IIETEC 2008 Conference*, April 15-16, Sohar University, Oman, 2008, pp.3-10.

4. **Ayyoub A. Moghanjoughi**, Sabira Khatun, Borhanuddin B. M. Ali, Raja S. A. R. Abdullah, "QoS based Fair Load-Balancing: Paradigm to IANRA Routing Algorithm for Wireless Networks (WNs)", *Proceeding of the 11th IEEE International ICCIT 2008 Conference*, December 25-27, Khulna, Bangladesh.

5. **Ayyoub A. Moghanjoughi**, Sabira Khatun, Borhanuddin B. M. Ali, Raja S. A. R. Abdullah, "Performance Analysis of IANRA Routing Algorithm for Load-Balancing in

Wireless Mesh Networks", *International Conference on Rural Information and Communication Technology*, 17th-18th June, Indonesia, 2009.

6. Sabira Khatun, **Ayyoub A. Moghanjoughi**, Borhanuddin B. Mohd Ali, Raja S. A. R. Abdullah, "IANRA: An Intelligent Route Discovery Framework for Load-Balancing in Wireless Networks", *Pameran Reka cipta, Penyelidikan dan Inovasi 2009 (PRPI'09),* July 28-30, 2009, Universiti Putra Malaysia. **(Gold Medal)**