Brunel University
School of Engineering and Design
Electronic and Computer Engineering Department

Intelligent MANET Optimisation System

by
Nagham Saeed

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Abstract

In the literature, various Mobile Ad hoc NETwork (MANET) routing protocols proposed. Each performs the best under specific context conditions, for example under high mobility or less volatile topologies. In existing MANET, the degradation in the routing protocol performance is always associated with changes in the network context. To date, no MANET routing protocol is able to produce optimal performance under all possible conditions.

The core aim of this thesis is to solve the routing problem in mobile Ad hoc networks by introducing an optimum system that is in charge of the selection of the running routing protocol at all times, the system proposed in this thesis aims to address the degradation mentioned above. This optimisation system is a novel approach that can cope with the network performance's degradation problem by switching to other routing protocol. The optimisation system proposed for MANET in this thesis adaptively selects the best routing protocol using an Artificial Intelligence mechanism according to the network context.

In this thesis, MANET modelling helps in understanding the network performance through different contexts, as well as the models' support to the optimisation system. Therefore, one of the main contributions of this thesis is the utilisation and comparison of various modelling techniques to create representative MANET performance models. Moreover, the proposed system uses an optimisation method to select the optimal communication routing protocol for the network context. Therefore, to build the proposed system, different optimisation techniques were utilised and compared to identify the best optimisation technique for the MANET intelligent system, which is also an important contribution of this thesis.

The parameters selected to describe the network context were the network size and average mobility. The proposed system then functions by varying the routing mechanism with the time to keep the network performance at the best level. The selected protocol has been shown to produce a combination of: higher throughput, lower delay, fewer retransmission attempts, less data drop, and lower load, and was thus chosen on this basis. Validation test results indicate that the identified protocol can achieve both a better network performance quality than other routing protocols and a minimum cost function of 4.4%. The Ad hoc On Demand Distance Vector (AODV) protocol comes in second with a cost minimisation function of 27.5%, and the Optimised Link State Routing (OLSR) algorithm comes in third with a cost minimisation function of 29.8%. Finally, The Dynamic Source Routing (DSR) algorithm comes in last with a cost minimisation function of 38.3%.

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ABR	Associativity-based Routing
AI	Artificial Intelligence
AMRoute	Ad hoc Multicast Routing
ANFIS	Adaptive Network Fuzzy Inference System
ANN	Artificial Neural Network
ANSI	Ad hoc Networking with Swarm Intelligence
AODV	Ad hoc On Demand Distance Vector
AUC	Area Under the Curve
CAMP	Core-assisted Mesh Protocol
CBT	Core-based Tree
CEDAR	Core Extraction Distributed Ad hoc Routing
CGSR	Clusterhead Gateway Switch Routing
CRDF	Cross-layer Route Discovery Framework
DARPA	Defense Advance Research Projects Agency
DREAM	Distance Routing Effect Algorithm for Mobility
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
EA	Evolutionary (computation) Algorithm
FTP	File Transfer Protocol
GA	Genetic Algorithm
GloMo	Global Mobile Information Systems
GPS	Global Positioning System
HSR	Hierarchical State Routing
IETF	Internet Engineering Task Force
I-MAN	Intelligent Mobile Ad hoc Network
IoT	Internet of Things
IP	Internet Protocol
LAR	Location Aided Routing
MANET	Mobile Ad hoc NETwork
MLP	Multi-layer Perceptron
MOSPF	Multicast Open Shortest Path First
MPRs	MultiPoint Relays
MS	Mean Square
NF	Neuro-fuzzy
NTDR	Near-term Digital Radio
ODMRP	On Demand Multicast Routing Protocol
OLSR	Optimised Link State Routing
PAN	Personal Area Network
PC	Personal Computer
PCMCIA card	Personal Computer Memory Card International Association
PDA	Personal Digital Assistant
PIDIS	Protocol-independent (packet) Delivery Improvement Service
PRDS	Priority-based Route Discovery Strategy

PRNET	Packet Radio Networks
PSO	Particle Swarm Optimisation
RA	Retransmission Attempt
RBF	Radial Basis Function
RE	Regression Equation
RIP	Routing Information Protocol
RMSE	Root Mean Square Error
RoSAuto	Routing Strategy Automation
SI	Swarm Intelligence
SURAN	Survivable Adaptive Radio Networks
TSK	Takagi-Sugeno-Kang
TTL	Time To Live
UML	Unified Modeling Language
VANETs	Vehicular Ad hoc Networks
WMN	Wireless Mesh Network
XML	Extensible Markup Language
ZRP	Zone Routing Protocol

Author's Declaration

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all the information sources and literature used are indicated in the thesis.

Signature of Student

Chapter 1

Introduction

1.1 Introduction

Day after day, wired networks are handing out other applications to wireless networks that provide similar services to wired networks with unique mobility characteristics. Wireless networks are quickly emerging as an important innovation and becoming an essential component of contemporary daily life. The wireless network is ideal in that it not only fulfils an entire set of user requirements, but also provides service at an acceptable standard.

Mobile Ad hoc NETwork (MANET) [1] is a self-configured infrastructure-less network of wireless mobile devices. This network has great advantages during national crises, disaster relief, and rescue operations. With wireless networks, the set of mobile nodes at arbitrarily locations can be interconnected through routing protocols. Therefore, a large number of routing protocols have been proposed to support the communications in MANET. Many protocols were developed, and many techniques from other disciplines were also utilised to create new routing protocols to achieve the user and the network requirements. However, until now there has been no optimal protocol(s) that is expected to produce good performance in all network contexts, as each protocol was developed based on particular assumptions.

This thesis starts by presenting a survey of the various MANET routing protocol classifications to provide a better understanding of the MANET routing protocols. Then, a survey of optimisation techniques implemented in MANET routing protocols is given to describe the pervious attempts in routing optimisation. Thereafter, a novel design for an optimisation system is presented to allow the optimisation of the proposed network. In addition, those Artificial Intelligence (AI) techniques applicable to the problem are also reviewed. Finally, as is the goal of this thesis, a MANET routing protocols optimisation system for wireless communication networks, based on the aforementioned AI techniques, is developed.

In this chapter, an overview of the entire thesis will be provided. The motivation for the research is briefly presented in Section 1.2, with the research's overall aim and objectives identified in Section 1.3. Next, technical challenges are highlighted by Section 1.4. The main scientific contributions are then presented in Section 1.5, and the thesis' scope detailed in Section 1.6. Finally, this chapter is concluded with an outline of the thesis in Section 1.7.

1.2 Motivation

Two issues are considered in this research as the motivation behind designing an optimisation system for MANET routing protocols. The first issue is related to wireless networks in general, and the second is related to the particular area in MANET, that is the routing problem, as described below.

1.2.1 Better MANET

The research in MANETs should grow to match the rapid evolution of wireless communication technologies. Providing the users with acceptable levels of service is a goal which will have to be met by research into MANET optimisation.

1.2.2 MANET Routing Problems

In MANET, each node has the freedom to join, leave, and move around the network. This movement creates a highly dynamic environment that effects packet routing. Therefore, efficient packet routing is one of the most challenging problems in MANETs. The objective of routing is to guide packets through the communication subnet to their final destinations. As a result of working on this problem, numerous routing protocols [1]-[6] have been proposed in the literature. The aim is to find the most suitable path from source to destination, with the ultimate goal being to establish efficient route and efficient message exchange within MANET.

The most suitable path could be either the shortest path [7], which can be selected from multi-paths, or the reliable path [8], which has less congestion and a more stable network connection. However, there are still two other major problems with the current MANET routing schemes, as described by the following.

First*, *each identified routing protocol addresses the objectives of its development

From the literature reviewed, it can be concluded that the mobility causes frequent changes in MANETs topology which have led to the design of various routing schemes, with each scheme aiming at a particular type of MANET topology. Each protocol has different objectives and focuses on solving the problems for the definite context conditions. For example, before designing a routing protocol, the network should be identified as a flat or cluster mobile network, and also have a particular network mobility level (low, medium, or high).

The above means that each routing protocol is specifically designed to achieve high performance in a particular MANET context. Heretofore, to the best of our knowledge, there is no optimum routing protocol that can handle all expected network context changes and is proven to maintain an optimum network performance given these changes. However, there are many protocols that can be optimal for a specific situation.

Several performance simulations, comparisons, and evaluations [9]-[16] were done to judge the routing protocols behaviour within different contexts, proving that some routing protocols could not maintain the network performance at an acceptable level with the changes in the context. For example, a protocol that is designed for a small network is not good for a large network, and the protocol that is designed for low mobility is, predictably, often poor for high mobility situations.

Second, during a MANET life cycle, only one routing protocol can be utilised.

The routing protocol responsibility is not only restricted by the need to connect MANET nodes together for communication, but also to keep the communication flowing at an acceptable level at all times. For instance, consider a MANET that starts with a large number of nodes in low mobility. A routing protocol R1, which was designed with such a context in mind, successfully maintains the optimum performance. However, consider now that due to certain circumstances, the number of nodes drops dramatically while node mobility rises sharply (a typical scenario in many emergency situations), resulting in a severe degradation of protocol R1 performance. However, the existing MANET routing protocol R2, which was designed with the latter scenario in mind, cannot be deployed to help in this situation as the MANET is already running with R1.

As such, a MANET that employs a specific routing protocol cannot benefit from the advantages of other routing protocols given changing conditions. In the performance evaluation literature [9]-[16], a selected group of routing protocols with the same network characteristics were compared. Each protocol's respective strengths and weaknesses were then identified and explained. This literature focused on evaluating the protocols without suggesting any solution when the protocol degraded, although comparisons of weaknesses and strengths were also made. Nonetheless, this literature has proven to be a useful source of information for users of a network with the same routing characteristics who wish to avoid protocol weakness

It is important to note that, heretofore, there has been no effort to comprehensively list *all* of the available routing protocols and evaluate them with the same performance parameters.

1.3 Research Aim and Objectives

The overall aim of this thesis is to design and develop a novel intelligent routing protocol optimisation system to be implemented in a mobile Ad hoc network. The goals of this research are addressed through the following objectives:

1. Review and study MANET routing protocols to gain an understanding of issues associated with this field;

2. Survey the optimisation techniques that have been implemented in Ad hoc routing protocols to identify the related optimised network with the proposed intelligent optimised system;

3. Review the area of Artificial Intelligence techniques to understand their principles and operations, as applied to the subject of this study;

4. Develop an architectural design for a communication network monitoring system that incorporates a context-aware intelligent selection module;

5. Build the proposed system, which involves five tasks;

   a. Create the references (data) needed that represent MANET performance. This objective will be achieved through creating a group of simulations with the support of the Opnet™14 software package; the results of the simulation will then be collected and arranged to create models with the support of the MATLAB™ software package.

   b. Investigate and study a group of modelling techniques with the support of the MATLAB™ software package and Essential Regression software package, and then select the most appropriate one.

   c. Investigate and study a group of optimisation techniques with the support of the MATLAB™ software package and then select the most appropriate one.

   d. Create the selected Modeller and the selected Optimiser in the Opnet™14 software package, utilising C++ language.

   e. Create the selection and the switching mechanism in C++ and embedded in the Opnet™14 software package.

6. Implement the proposed system in a case study simulation scenario in the Opnet™14 software package; and

7. Analyse, compare, and validate the simulation scenario results.

1.4 Challenges

To create the intelligent optimisation system and satisfy the thesis objectives, there are a number of technical challenges to overcome. The main challenges are as follows:

1. Determine the context-aware parameters that should be considered in the design;

2. Select the Artificial Intelligence techniques that support the final system design;

3. Embed the selected Artificial Intelligence techniques in the MANET;

4. Generate a decision function (the cost function) to be used in finding the optimum routing protocol for the assessment process;

5. Create a switching technique inside each network node that enables the node to switch from one routing protocol to another;

6. Develop a mechanism that assigns the optimal protocol to the network, and the time at which all the network nodes should implement the switching; and

7. Decide the optimum MANET topology that is compatible with the intelligent system.

1.5 Main Contributions

There are six main contributions of this thesis which are summarised in the following sections.

1.5.1 Comprehensive Taxonomy of Mobile Ad hoc Routing Protocols

Prioritising routing and considering it a key issue for a better MANET performance has resulted in the development of a large number of MANET routing protocols in recent years. Each routing protocol is designed for specific characteristics of MANET. The taxonomy listed in this thesis will make the researchers aware of the routing protocol classification available in the area of MANET. This taxonomy draws an ostensible “big picture” of those available routing protocol classifications that depend on the routing characteristics. Such knowledge of the available routing classifications assists in guiding researchers to the right choice of routing protocol. Furthermore, this thesis contributes a new classification to the traditional taxonomy, which depends upon the routing metric.

1.5.2 Creating and Comparing MANET Models

In this thesis, the modelling concept implemented differs from most of the existing MANET modelling research. Whereas most of the existing research involved mathematical equations to represent MANET models, in this research, the models were developed by the measurement of network performance. Three techniques were utilised to create MANET performance models: neural network, neuro-fuzzy, and empirical equations. The three models were therefore generated for the same measurement. Each performance model represents the network behaviour against the selected context-aware parameters. This thesis presents, for the first time, a quantitative comparison between the techniques mentioned based on the Root Mean Square Error (RMSE). This comparison evaluates the modelling techniques and determines the best modelling technique for MANET performance.

1.5.3 Optimisation Techniques in MANET

Two optimisation techniques are explored in detail in this thesis, the Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO) techniques. The two techniques were utilised in previous MANET optimisation studies. In this thesis, for the first time, a quantitative comparison between GA and PSO in optimizing MANET routing protocol is presented based on the minimum Mean Square for the performance parameters. This comparison evaluates the optimisation techniques to determine the best technique for MANET optimisation.

1.5.4 Detailed Design and Implementation of the Optimisation System

This thesis presents a novel, self-organised approach for selecting the optimum routing protocol based on the network history. The system orders the network to switch protocols to maintain the network performance in an acceptable level. A novel design for the routing protocols intelligent optimisation system is presented in this thesis. Also, the system requirements are explained in further detail.

1.5.5 Quantitative Evaluation of the Network Performance

After modifying the original nodes to satisfy the system requirements, the invented intelligent system was simulated with a mobile Ad hoc network. To measure the efficiency of the proposed approach, a comparison between networks operated with other routing protocols was made. The networks were simulated using the same case study scenario.

In this thesis, a novel technique has been proposed to calculate the overall performance of the MANET and to evaluate the network performance, quantitatively. This technique is based on normalizing the network performance parameters, then feeding the results through the cost minimisation function to determine the best cost for the network.

1.5.6 Test the Topology Packets Inter-Arrival Time

One of the major issues in implementing the system proposed by this thesis is the technique to update the network nodes. Two types of information packets have been utilised to satisfy this system requirement: the periodical Topology packets and the Decision packets. Furthermore, to develop the invented system, the Inter-Arrival time for the Topology packets has been tested and the best period selected.

1.6 Thesis Scope

Having drawn upon paradigms from various sources, the resulting research is of a multidisciplinary nature which involves the cross-fertilisation of ideas for optimisation, Artificial Intelligence (AI), and wireless networking, among others. Therefore, it was necessary to outline a clear scope to successfully accomplish the objectives in the given time frame. This scope is summarised in Figure 1.1. The examples given in each domain of research, although not as exhaustive as seen in the figure, are as follows:

1. In terms of optimisation that considers any characteristic or technique that improves the network performance, in this thesis, three different types of optimisation, self-organisation, modelling, and prediction, have been considered.

2. In terms of the underlying wireless networks, the goal of this research is to solve the routing problems in mobile Ad hoc networks. Investigating other wireless network problems, and the application of the novel optimised system to these infrastructures, is considered beyond the scope of this thesis.

3. In terms of Artificial Intelligence (AI), there are several powerful techniques in the AI field. In this thesis, four well known techniques have been investigated; artificial neural network (ANN), neuro-fuzzy (NF), Genetics Algorithms (GA), and Particle Swarm Optimisation (PSO). Investigating other techniques is considered beyond the scope of this thesis.

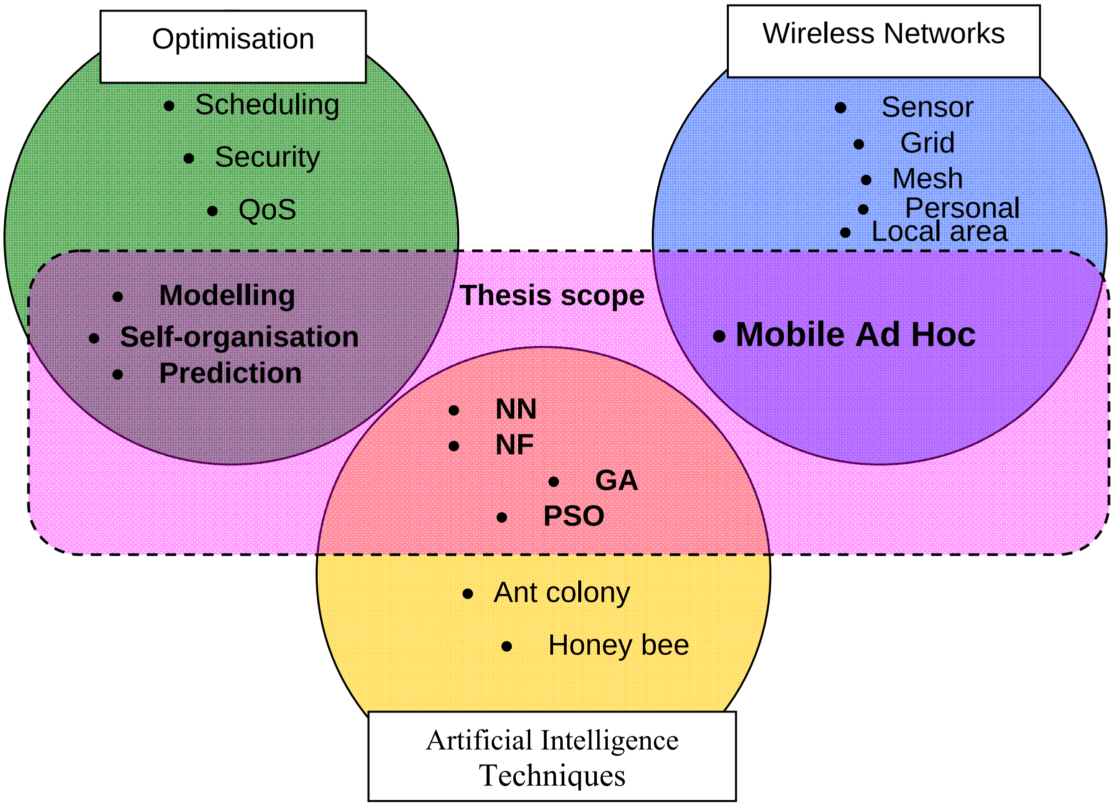

Figure 1.1: Thesis scope.

1.7 Thesis Outline

The work presented in this thesis is organised into nine chapters. Each chapter starts with a brief introduction that highlights the main contributions and provides an overview of that chapter. At the end of each chapter, a brief conclusion and list of references is presented. The next eight chapters contain more detailed information about the theoretical background and technical development of the Intelligent-Mobile Ad hoc Network (I-MAN) optimisation system.

In Chapter 2, brief definitions of mobile networks are presented, which include definitions for Internet and Ad hoc networks, with detailed background information about MANET. The routing protocols for wired networks are also defined and clarified in this chapter. Various MANET routing protocol taxonomies are then listed based on network characteristics. Each protocol characteristic is subsequently defined, explained, and summarised at the end of the chapter.

Next, in Chapter 3, a survey of the optimised routing protocols is presented. The protocols in this chapter are classified according to three optimisation criteria: either a routing metric that is considered in the design, a prediction technique utilised, or an Artificial Intelligence technique utilised. Any related work is then compared to the thesis in terms of objectives, models, prediction, and design. The chapter is concluded with a brief summary and a discussion.

In Chapter 4, the I-MAN routing protocols optimisation system design is illustrated and the system elements are defined, with the task sequence for each element explained thereafter. The techniques for the routing protocols considered in the I-MAN optimisation system implementation stage are explained in further detail. Each protocol's weaknesses and strengths are also explained in the chapter. The chapter is concluded with a comparison between the routing protocols and a summary.

Following this, the network configuration setting is determined and the MANET network simulated with the selected routing protocols in Chapter 5. The results are first presented in a 2D graph, and then organised into more elaborate 3D graphs. The simulation results are discussed in detail, with the network performance indicators for each routing protocol evaluated for the entirety of the simulation's duration. A short summary of each routing protocol's performance concludes the chapter.

In Chapter 6, the general empirical model is defined and the Regression Equation (RE) models are explained in detail. The chapter also defines AI modelling methods and explains ANN and NF at greater length. The MANET models presented in this chapter are created using the three previous modelling techniques (RE, ANN, and NF). A quantitative comparison to select the best modelling technique based on RMSE is presented in this chapter as well, and the chapter closes with a short summary of these results.

In Chapter 7, two intelligent computing optimisation techniques are defined: Evolutionary Computation and Swarm Intelligence. One technique was selected from each method to be tested; GA from the first, and PSO from the second. A detailed description of the GA and its operations is presented herein. The general characteristics of the PSO and its operation are also subsequently presented. Next, a brief comparison between the two techniques is undertaken. The MANET GA Optimiser and MANET PSO Optimiser are then configured and implemented module results for each Optimiser recorded. The validation table in the chapter confirms that MANET routing protocols lose part of their efficiency when the network context is changed. However, by observing the cost function for each technique, the best optimisation technique can be identified, and the chapter closes with a short summary of these results.

Chapter 8, furthermore, addresses two important issues that should be considered in implementing the I-MAN routing protocols optimisation system in MANET. The final components for the optimisation system and the time sequence of the components' operation are described. The role for each component is described in detail. The embedding procedure for each component in MANET is also illustrated; then a case study with a defined simulation environment and the experiment configuration is presented. The results are analysed, compared, discussed, and then evaluated. The effect of Inter-Arrival Time (T_{IA}) on network performance is further analysed and evaluated. I-MAN routing protocols optimisation system limitations are listed in this chapter, which concludes with a discussion of the findings.

Finally, in Chapter 9, the overall findings of the thesis are summarised. This chapter highlights areas currently unexplored and indicates potential directions for further research.

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Chapter 2

MANET Routing Protocols

2.1 Introduction

In recent years, network structure has changed significantly; that the only known and available network 40 years ago was the wired network. However, as mobility needs continue to grow, wireless networks have appeared as an efficient solution to increasing service demands. The development in wired networks has paled in comparison to the tremendous increase in wireless networks. This has happened in spite of the limitations of wireless network techniques, such as the changes in network topology, a high error rate, power restrictions, bandwidth constraints, and issues with link capacity [1]-[2].

These limitations are the result of the freedom of movement in mobile wireless networks, as mobile wireless networks are dynamic and feature multi-hop topology. As such, researchers have stepped forward to solve these challenges, putting substantial effort behind inventing new technologies. They have hence addressed the problems with innovative solutions to support the robust and efficient operation of mobile wireless networks. One of the main areas of research has been routing technology which will route packets from source to destination.

The focus of this chapter is both describing the mobile network and its types, and defining network routing. The main contribution herein is the presentation of different classifications of Ad hoc routing protocols according to different criteria. The various classifications give a better overview of the MANET routing protocols. The classifications also show the researchers' settings before designing a routing protocol and, at the same time, give an overview for existing routing protocols, as these classifications are more beneficial than a lengthy listing of previous routing protocols alongside the updated ones.

In Section 2.2, two mobile network topologies, the mobile Internet network and the mobile Ad hoc network, are introduced. The following section, Section 2.3, then explains the routing protocols in wired networks and their types. Wireless network routing problems are also identified here. In Section 2.4, different routing protocols taxonomies are presented, and finally, Section 2.5 consists of the summary and conclusions from this chapter.

2.2 The Mobile Network Topology

In any network, each application involves sending/receiving information from one node (a personal computer, laptop, PDA, or mobile phone) to another. This application could be in the form of FTP files, emails, or video. The information is segmented and sent as data packets from node A (the source) to node B (the destination), with the data packets specifically routed to reach B. In order to transmit and receive data packets, there are two types of network topology, as explained below.

2.2.1 Mobile Internet Network

The nodes of this type are supported by the Internet, as shown in Figure 2.1. The mobile Internet nodes are classified either as a mobile router or as a mobile node. Within the Internet community, mobile nodes are either wired by a dial-up line or broadband directly to a router in a fixed network, or mobile node that is roaming and connecting wirelessly through various means (fixed or mobile router) to the Internet. The backbone-fixed network consists of routers which are the access points (the base station) that connect to the Internet nodes. As such, part of the mobile Internet network is fixed and has infrastructure. This mobile node could be connected to a mobile router and become part of the mobile network; in turn, the routers are connected wirelessly to a fixed network, as shown in Figure 2.1 [3].

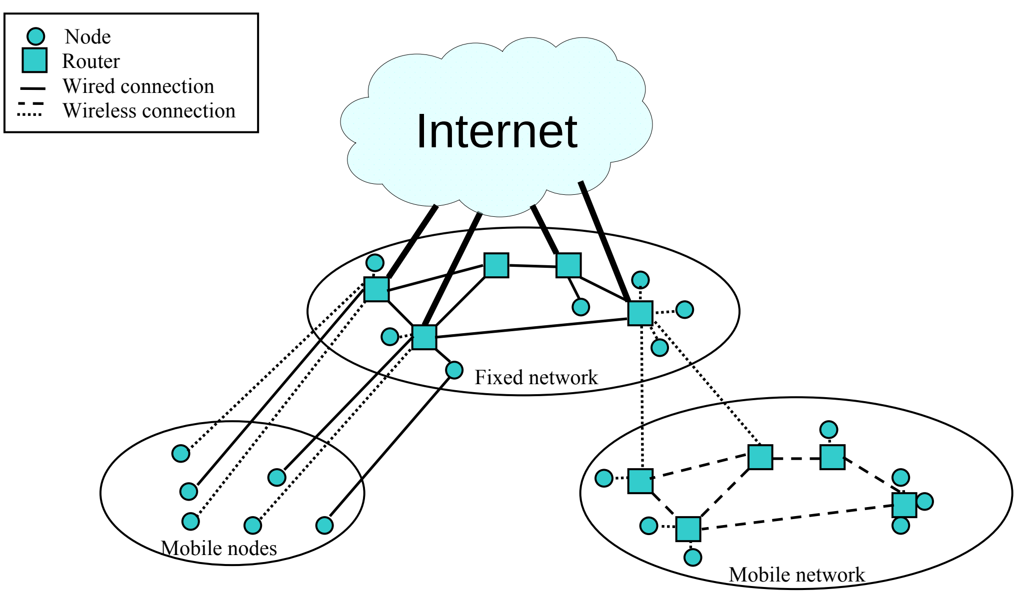


Figure 2.1: Mobile Internet classifications.

The Mobile Internet Protocol (IP) technology has been presented to support routing for mobile nomadic nodes. However, core network functions, such as hop-by-hop routing, still rely upon pre-existing routing protocols operating within the fixed network [4]. The mobility of mobile Internet network is limited; thus, the network must stay within transmission range to maintain the Internet connection [5]. Under these circumstances, the mobile Internet node in this network would be either a router or a host.

2.2.2 Mobile Ad hoc Network (MANET)

The vision of Ad hoc network is a wireless network in which users can move anywhere, anytime and still remain connected with the rest of their group. Theoretically, if one node has access to the Internet, this means that all group nodes have the potential to remain connected with the world at large.

The successful implementation of Ad hoc wireless networking technology presents a unique set of challenges that differ from those of traditional wireless systems and wired networks [6]. One of the challenges is the routing protocol in the Ad hoc network.

MANET is one of the Ad hoc networks that cover a variety of network paradigms for specific purposes, such as sensor networks, vehicular networks, underwater networks, underground networks, personal area networks, and home networks.

MANET promises a broad range of applications in civilian and commercial arenas, including board meetings and conference calls. MANET also has important applications in national crisis situations such as flood and earthquake, in which MANET can be utilised for disaster relief and rescue operations as in the case of fires. Finally, MANET may be beneficial in military areas such as in battlefield communications.

The lack of a MANET capacity (in terms of reliable data rate) has stunted the commercialization of many MANET types [7].

2.2.2.1 MANET Functionality

MANET is an autonomously self-organised network that does not have infrastructure support. Simply, MANET needs two or more mobile “nodes” to be created; these nodes can be a laptop, PDA, or/and mobile phone, as shown in Figure 2.2. Nodes may be located on airplanes, ships, trucks, cars, or people. MANET nodes move in an Ad hoc way and are free to roam about arbitrarily, having no restriction on their movements. The network may therefore experience rapid and unpredictable topology changes.

Additionally, because nodes in a mobile Ad hoc network normally have limited transmission ranges, some nodes cannot communicate directly with each other, and as such, the Ad hoc nodes should route the packets with the support of a particular routing technique. MANET nodes are both routers and hosts simultaneously. Each node should be logically capable of performing the routing functionality (both route packets and act as a router), as well as transmitting and receiving functionality (receiving packets as a destination node) and transmitting (transmitting packets as a source node) [7].

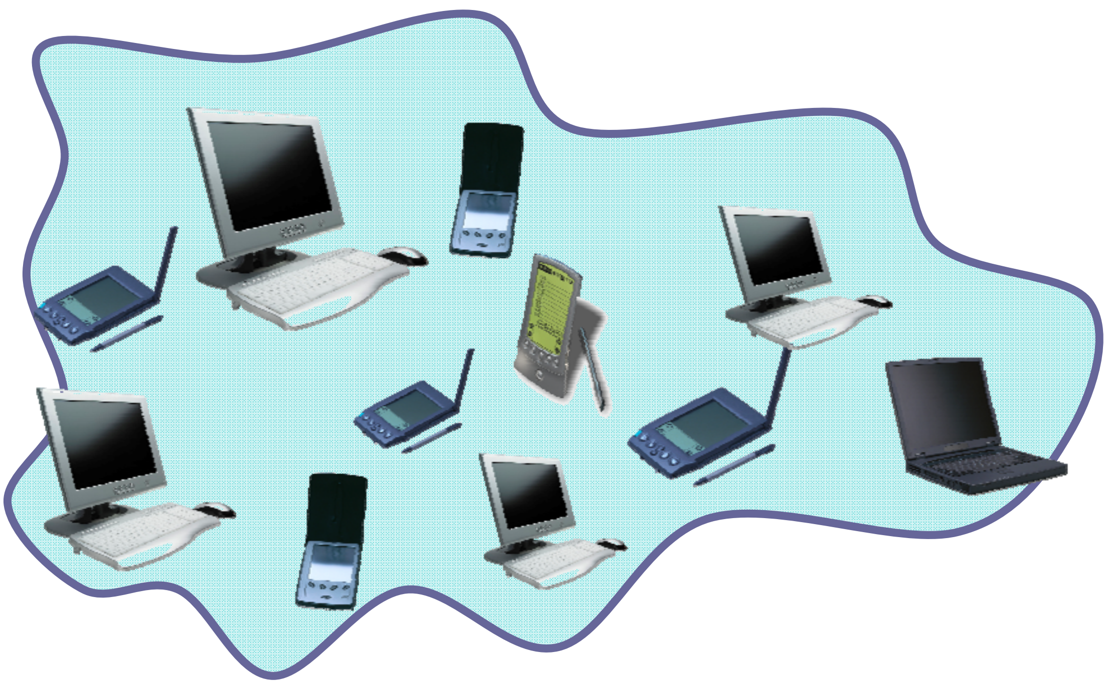


Figure 2.2: **M**obile **A**d hoc **NET**work.

2.2.2.2 Ad hoc Network History

The first Ad hoc generation goes back to 1972 when the Defense Advance Research Projects Agency (DARPA) [8] adopted a project called Packet Radio NETworks (PRNET) [9]. The project was primarily inspired by the efficiency of packet switching technology such as bandwidth sharing and store and forward routing. Also, the project was based on the possibility of applying the packet switching technology in a mobile wireless environment. The PRNET network nodes and devices (repeaters or routers) were all mobile, although mobility was limited. These protocols were considered among the most significant advancements in the field up to this point.

The packet switching technology is a digital network communications method that groups all transmitted data, irrespective of content, type, or structure, into suitably-sized blocks called *packets*. The network over which the packets are transmitted is a shared network which routes each packet independently from all others and allocates the transmission resources as needed. The principal goals of packet switching are to optimise the utilization of available link capacity, minimize response times, and increase the robustness of communication [10].

The second generation of Ad hoc networks emerged in the 1980s, when Ad hoc network systems were further enhanced and implemented as a part of the Survivable Adaptive Radio Networks (SURAN) program [11]. This program provided a packet-switched network in an environment without infrastructure, such as a mobile battlefield similar to that shown in Figure 2.3. The program was ultimately successful, improving the performance of radios by making them smaller, cheaper, and more resilient to electronic attacks.

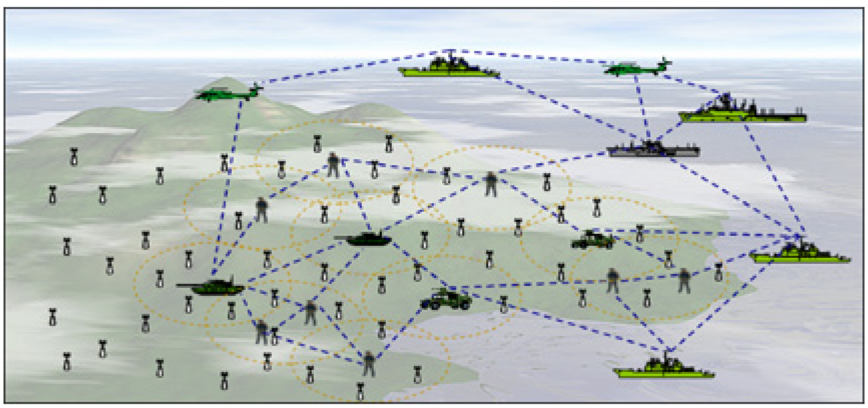


Figure 2.3: MANET in battle field environment [12].

Later, this advance in microelectronic technology assisted in the integration of nodes and network devices into a single unit called the Ad hoc node. Subsequently, the IEEE 802.11 subcommittee adopted the term "Ad hoc networks" to refer to the wireless interconnection of such Ad hoc nodes.

In the 1990s, the concept of commercial Ad hoc networks became viable with the advent of notebook computers and other communications equipment. Global Mobile Information Systems (GloMo) [13] and the Near-term Digital Radio (NTDR) [14] are just some of the results of the previously built Ad hoc networks. Whereas GloMo was designed to provide an office environment with Ethernet-type multimedia connectivity, anywhere and anytime, in handheld devices, NTDR is a two-tier, self-organised Ad hoc network that uses clustering and Link State routing. As such, NTDR was the only "real" non-prototypical Ad hoc network that was in use at the time.

Active research work on Ad hoc networks started in 1995, in a conference session of Internet Engineering Task Force (IETF) [15]. Early discussions centred on military tactical networks, satellite networks, and wearable computer networks, with specific concerns being raised relative to the adaptation of existing routing protocols supporting IP networks in a highly dynamic environment. By 1996, this work had evolved into the Mobile Ad hoc Network (MANET) and finally to the charter of the MANET working group of the IFTF in 1997. The task of the MANET working group is to specify standard interfaces and protocols for the support of IP-based internet over Ad hoc networks. The development of routing within the working group and the larger community resulted in the invention of reactive and proactive routing protocols.

Following these developments, Ad hoc networking technology was applied to service applications ranging from home wireless to wide area peer-to-remote networking and communications. An example of that effort is the Personal Computer Memory Card International Association (PCMCIA card) [16]. This card is an international standard body that defines and promotes the PC Card and the Express Card standards. Although the organization's name refers to memory cards, its standards are not limited to memory devices; these cards can be used for wireless connectivity, modems, and other functions in laptop/notebook PCs that may be lacking them natively. The second example is the Bluetooth technology [17], which is a wireless protocol for exchanging data over short distances (using short length radio waves) from fixed and mobile devices. The network created is called a Personal Area Network (PAN).

As wireless devices are getting smaller, cheaper, and more sophisticated, they are also becoming more ubiquitous. Given the increasing demands of users, communication companies continue to search for inexpensive ways to maintain the devices connected. Ad hoc networks, as such, have appeared as an appealing solution to this connectivity problem.

2.3 Routing Protocols

The routing aspect in a network has a fundamental value as it is the means of communication and information transfer. Routing is thus one of the main networking functions of a wireless network. In a wired or wireless network, the routing principle is such that a source node wants to communicate with a destination node that is not in the source covering range. In the case that the destination node is far from the source, to establish the connection, the source will try to find a route to the destination node through other nodes, this packets routing process called routing protocol. The data packets will be send out when the routing protocol establishes a path between the source and the destination. Several routing algorithms and protocols have been developed to solve this routing problem.

The following sections show the types of wired and wireless network routing protocols.

2.3.1 Routing in Wired Network

Historically, the wired network was invented before the wireless network, and thus the wired network routing protocols were introduced first. Generally, the most popular routing algorithms in the wired network are Distance Vector and Link State routing algorithms, as shown in Figure 2.4. These protocols find the shortest paths to destinations.

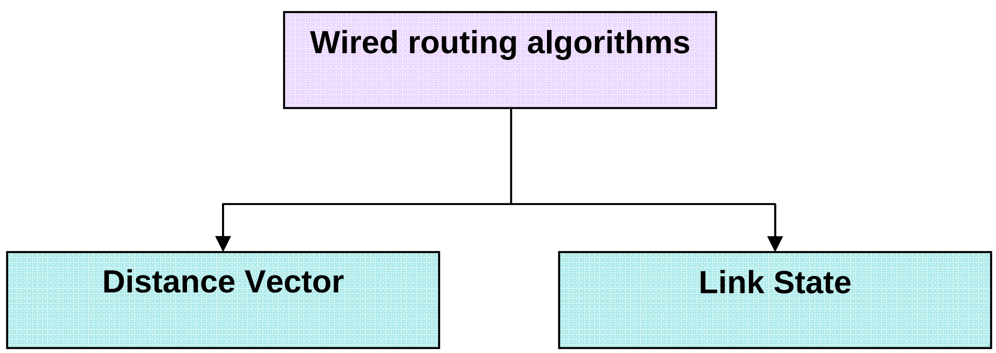


Figure 2.4: Routing protocol classifications for wired network.

2.3.1.1 Distance Vector Routing

The Distance Vector routing [2] algorithm is based on the Bellman-Ford algorithm [18] to calculate paths. The distance can be calculated based on metrics such as hop number. If multiple paths exist, the shortest one will be selected. Every router maintains a vector (routing table) that should be exchanged with other nodes. The vector stores all of the nodes' distance, cost (the hop distance), and path (the next hop) information to all destinations. The router then exchanges distance information with its neighbours to periodically update its routing table.

Distance Vector routing protocols are generally known to suffer from slow route convergence and a tendency to create loops in mobile environments. Slow convergence leads to the loop problem (explained in Section 4.3.4) as some routers continuously increase the hop count for particular networks. The well-known Routing Information Protocol (RIP) [19] is based on the Distance Vector algorithm.

2.3.1.2 Link State Routing

The Link State routing [2] algorithm overcomes the Distance Vector routing problem by maintaining global network topology information at each router. In Link State routing, different metrics can be chosen, such as number of hops. Shortest (or lowest cost) paths are calculated using the Dijkstra's algorithm [20]. Every node updates the current status of links to all routers in the network through periodic flooding. Therefore, if a change in link state occurs, the respective notifications will be flooded throughout the whole network. After receiving the notifications, all the routers re-compute their routes according to the fresh topology information. In this way, a router receives at least a partial picture of the whole network.

Unfortunately, the Link State advertisement scheme generates a larger routing control overhead than that of Distance Vector routing, as mobility entails frequent flooding. Also, in a large network, the transmission of routing information will ultimately consume most of the bandwidth and consequently block applications. Thus, reducing routing control overhead becomes a key issue in achieving routing scalability. The Open Shortest Path First (OSPF) [21] is an example of the Link State routing algorithm.

2.3.2 Routing in Wireless Ad hoc Network

Additional routing problems in Ad hoc networks are related to the no pre-existing infrastructure, the unpredictable network properties (such as the lack of static link quality), and the changeable network topology. Therefore, In Mobile Ad hoc NETworks (MANETs,) where every node has the responsibility to act as a route, routing is a particularly challenging issue as paths potentially contain multiple hops.

Merely implementing Distance Vector and Link State routing algorithms that perform well in wired networks is not efficient enough for MANET due to its dynamic features. Using the Distance Vector or the Link State routing algorithms in MANET means that the frequent topology changes will greatly increase the control overhead or suffer the slow route convergence and decay the algorithms' performance. If this issue is left unaddressed, the scarce MANET bandwidth is likely to be overused. Additionally, Distance Vector and Link State routing algorithms, when used for dynamic networks, will cause routing information inconsistencies and route loops.

Therefore, the routing protocols for wired networks must be modified to match the needs of Ad hoc networks in order to solve the previously mentioned problems. As a result, many Ad hoc routing protocols were invented. Surveys of routing protocols for Ad hoc wireless networks and MANET are presented in [5],[22],[23], and [24] and a more detailed description of mobile Ad hoc routing protocols found in the IETF (Internet Engineering Task Force) MANET working group [15].

2.4 MANET Routing Protocols Taxonomy

In the literature, there are many mobile Ad hoc routing protocols that should be categorized and classified. This classification helps in understanding, analyzing, comparing, and evaluating the routing protocols. Also, the classification can assist researchers and designers to differentiate the characteristics of the routing protocols and to find the relationships between them. The routing protocols cannot be included under one category or one classification, therefore, the known characteristics should be listed and the MANET routing protocols classified according to these attributes.

In this thesis, varies routing protocol classifications are presented that depend either on design philosophy, on network structure, or on the routing protocol characteristic (such as packet casting and network routing metrics).

2.4.1 Design Philosophy

Design philosophy is the most popular method to distinguish MANET routing protocols. It is based on how routing information is acquired and maintained by mobile nodes. Depending on design philosophy, Ad hoc routing protocols are represented by three main categories; proactive (also called Table Driven routing or Source routing), reactive (the other names are On Demand and Distributed routing), and hybrid (or Hierarchical routing), as shown in Figure 2.5. References [22] and [23] present surveys of the current routing protocols based on routing philosophy structure.

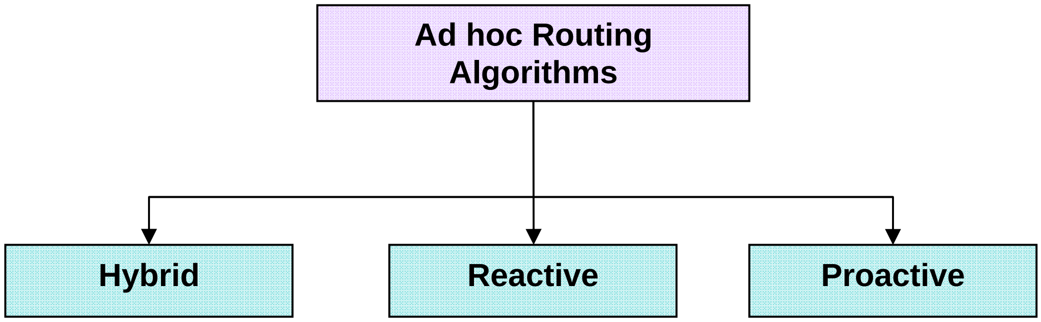


Figure 2.5: MANET routing protocol classifications depending on design philosophy.

2.4.1.1 Proactive Routing Algorithm

The proactive routing algorithm is the new version of the Internet Link State algorithm. The proactive routing algorithm [23] maintains routing tables that contain the information and the update for each node in the network. In order to maintain a consistent network view, for each topological change in the network, nodes should propagate updates throughout the network. Proactive routing protocols share a common feature—that is, background routing information can be exchanged regardless of communication requests. The Optimised Link State Routing (OLSR) Protocol [25] is an example of the proactive routing protocol that will be explained in further detail in Chapter 4.

The proactive algorithm has many desirable properties, especially for applications that include real-time communications and QoS guarantees, such as low latency route access and alternate path support and monitoring. The drawback of this technique, however, is the inefficiency of bandwidth utilization and power usage due to the overhead produced.

As such, most proactive protocols will not perform well given a high mobility rate or a large number of network nodes. Protocols in this category differ in terms of the number of tables they contain and how they update their information. Figure 2.6 illustrates the concept of proactive protocols. For example, if node A wants to send data to node D, then node A should search in a previously prepared topology table (stored on node A itself) to find D.

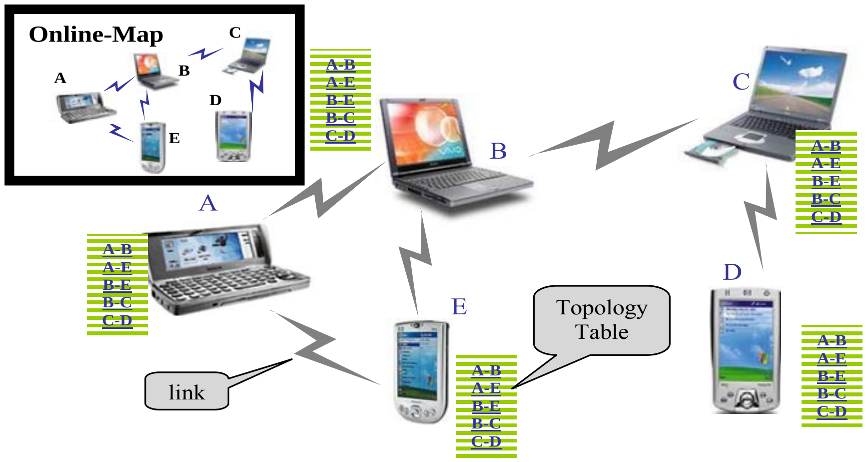


Figure 2.6: Proactive routing algorithm *Route discovery*.

2.4.1.2 *Reactive Routing Algorithm*

The reactive routing algorithm is the new version of the Distance Vector algorithm. The reactive routing algorithm [22] is characterized by *Route discovery* mechanisms and *Maintenance* mechanisms. *Route discovery* consists of *route request* and *route reply,* which differ from one protocol to another. The *Route discovery* mechanism is initiated when a source needs to communicate with a destination that it does not know how to reach.

As shown in Figure 2.7, when there is a request from node A to transmit data to node D, a route discovery process is begun by broadcasting to all nodes searching for node D. When D receives this message, it replies to the request to build the route to source A.

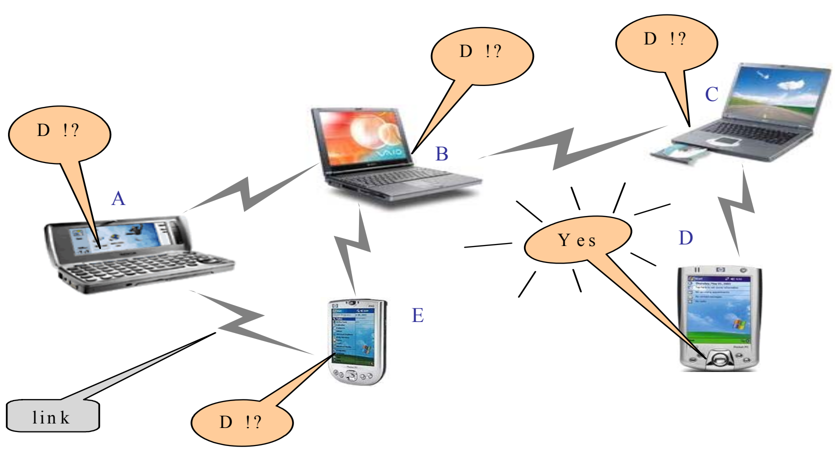


Figure 2.7: Reactive routing algorithm *Route discovery*.

Route discovery is usually in the form of a query flood. The *Route discovery* process is completed once a route is found or all possible route substitutions have been examined. Once a route has been established, as shown in Figure 2.8 by the green and yellow arrows representing the two routes discovered by source A to destination B, the *Maintenance* mechanisms will support routing in the network by keeping the data packets following the discovered route until either the destination becomes inaccessible along every path from the source, or the route is no longer desired. The destination may be rendered inaccessible for many reasons; for example, an intermediate node (which is part of the route to the destination) moves far from the network and is unable to participate, or one of the route nodes breaks down due to the node's battery life (as shown in Figure 2.8 by the purple arrows), or the node is busy with another application and does not want to consume power for communication. Also, link breakages can occur when the source node is moved in an attempt to maintain the connection with its destination.

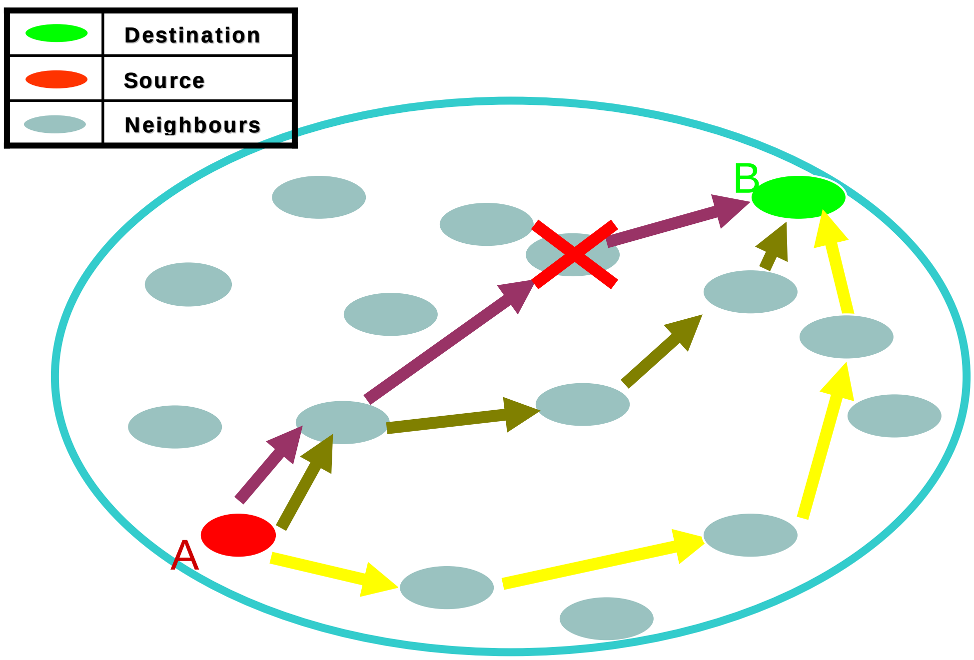


Figure 2.8: MANET reactive routing protocol.

When the intermediate node cannot deliver the data packet to its neighbour (next hop) due to a link breakage, the node's *Maintenance* mechanism will trigger a *route error* message to notify the source node and other nodes that certain nodes are no longer reachable. When the source receives this error message, it will try to solve the problem by either using other ready routes or establishing a new *Route discovery*.

The differences between the reactive routing protocols are in the implementation of the path discovery mechanism and its optimisation. Generally, reactive routing requires less overhead than proactive routing, but incurs a path discovery delay whenever a new path needed. The Dynamic Source Routing (DSR) protocol [26] and Ad hoc On Demand Distance Vector (AODV) Routing Protocol [27] are examples of reactive routing protocols. AODV and DSR techniques will be explained in further detail in Chapter 4.

2.4.1.3 Hybrid Routing Algorithm

Hybrid routing algorithms combine the two previous techniques (the proactive and the reactive) in an attempt to bring together the advantages of the two approaches. As such, hierarchical architecture is utilised in that these algorithms require an addressing system wherein the proactive and the reactive routing approaches are implemented at different hierarchical levels.

Such algorithms are designed to increase scalability by allowing the nodes closest to each other to connect and form a number of groups, as shown in Figure 2.9, and then assigning the group nodes different functionalities, both inside and outside the group, to reduce the *Route discovery* overhead. This is mostly achieved by proactively maintaining routes to nearby nodes and determining routes to far away nodes using a route discovery strategy. Both the size of the routing tables and update packets are reduced by including part of the network (instead of the whole network) within them, thus reducing control overhead in turn. The Zone Routing Protocol (ZRP) is an example of a hybrid routing protocol [28].

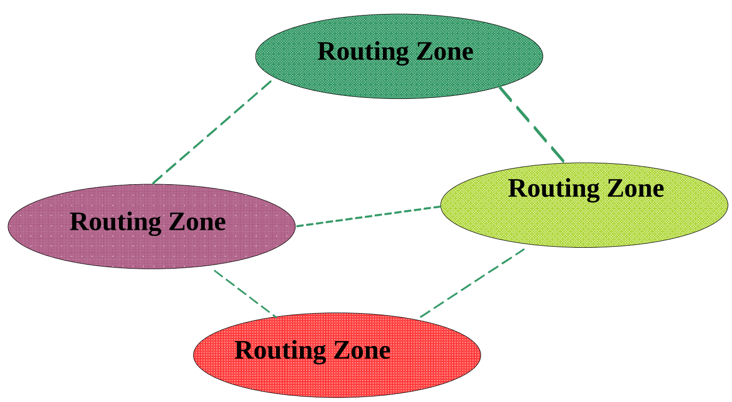


Figure 2.9: Hybrid-based routing algorithm.

2.4.2 Network Structure

In this section, a classification of the routing algorithms according to the network structure is provided. The routing algorithms that depend on the network structure consider two important elements which effect the routing operation: the nodes' mobility and the network scalability. The structure of Figure 2.10 blow is altered, as in Figure 2.5, but this is necessary in order to preserve the integrity of the diagram. Figure 2.10 categorizes the routing algorithms in Ad hoc networks into three broad categories: flat routing, geographic position information assisted routing, and hierarchical routing.

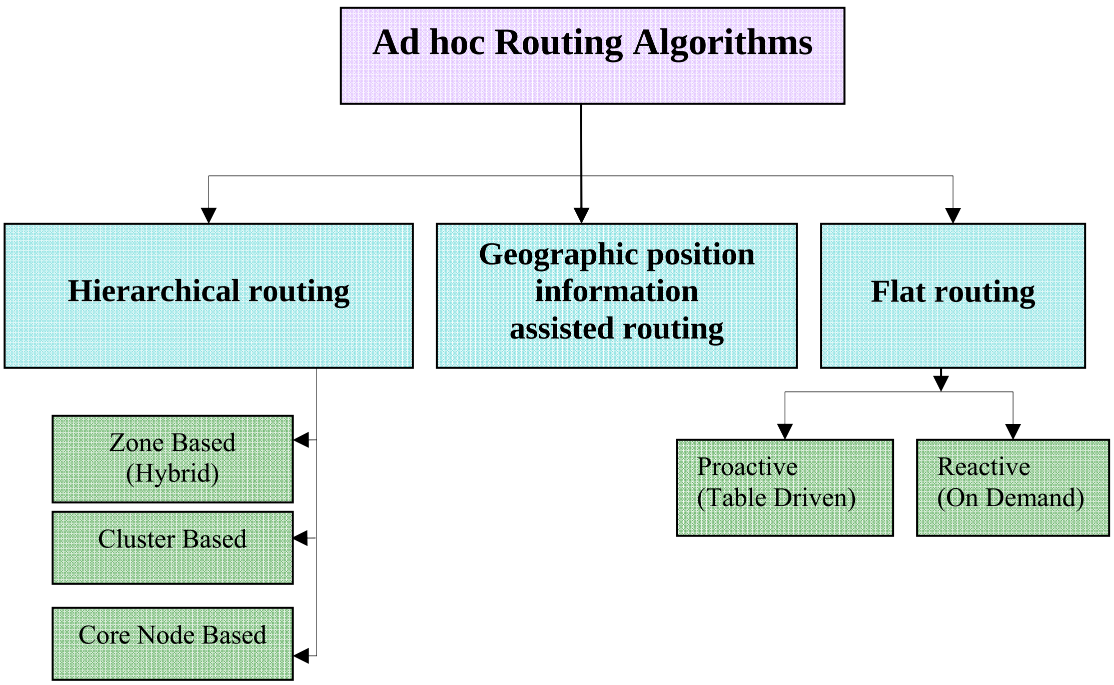


Figure 2.10: MANET routing algorithms classifications depending on network structure.

2.4.2.1 Flat Routing

Flat routing approaches [24] adopt a flat addressing scheme in that each participating node plays an equal role in routing. Therefore, the routing protocol is named as a *uniform* routing protocol in which all its mobile nodes have the same role, importance, and functionality. Flat routing schemes extend into two classes, proactive and reactive, according to their design philosophy (more detail about these two classes is given in Section 2.4.1). In a large network, flat reactive protocols are better than flat proactive routing protocols because of the reactive design philosophy; for example, if there is no communication, this means that there are no routing activities and no permanent routing information maintained at the network nodes.

The Optimised Link State Routing (OLSR) protocol [25], Dynamic Source Routing (DSR) protocol [26] and Ad hoc On Demand Distance Vector (AODV) routing protocol [27] are examples of uniform routing protocols.

2.4.2.2 Hierarchical Routing

In contrast to uniform flat routing, non-uniform hierarchical routing usually assigns different roles to network nodes (as explained in Section 2.4.1.3). Non-uniform routing approaches are related to hierarchical network structures to facilitate node organization and management. Normally, reactive algorithms are exploited to select the special nodes which carry out reactive management and/or routing functions.

In general, flat routing schemes become inefficient when the wireless network size increases due to link and processing overhead. Therefore, hierarchical routing, as shown in Figure 2.6, has been presented as an efficient solution to solve the problem and produce a scalable network. As shown in Figure 2.1, hierarchical routing has been implemented in wired networks for a long time.

Non-uniform hierarchical routing protocols can be further sorted into three subcategories: zone-based, cluster-based, and core-based. These protocols are categorized according to the organization of the mobile nodes, their respective management, and their routing functions [5].

A. Zone-based (Hybrid)

Figure 2.9 shows a zone-based hybrid routing algorithm; with this technique, each node has a local scope and different routing strategies are used, inside and outside the scope, as communications pass across the overlapping scopes. Given this flexibility, a more efficient overall routing performance can be achieved. Compared to maintaining routing information for all nodes in the whole network, mobile nodes in the same zone know how to reach each other with a smaller cost. In some zone-based routing protocols, specific nodes act as gateway nodes and carry out inter-zone communication. Therefore, the network will contain partitions or a number of zones. The Zone Routing Protocol (ZRP) [28] is a MANET zone-based hierarchical routing protocol.

B. Cluster-based

A cluster-based routing protocol is the most popular hierarchical routing technique. It uses a specific clustering algorithm for cluster head election in which mobile nodes are grouped into clusters by geographic proximity. Cluster heads then take responsibility on behalf of the cluster for membership management and routing functions. Cluster head Gateway Switch Routing (CGSR) [29] is an example of a cluster-based MANET routing protocol. The Hierarchical State Routing (HSR) protocol [30] also supports a multi-level cluster structure.

C. Core Node-based

In core node-based routing protocols, critical nodes are dynamically selected to compose a "backbone" for the network. The “backbone” nodes carry out special functions, such as the construction of routing paths and propagation of control/data packets. Optimised Link State Routing (OLSR) [25] and Core Extraction Distributed Ad hoc Routing (CEDAR) [31] protocols are typical core node-based MANET routing protocols.

2.4.2.3 Geographic Position Information Assisted Routing

Routing with assistance from geographic location information requires each node to be equipped with a Global Positioning System (GPS). This satellite system [32] provides reliable positioning, navigation, and universal timing services to worldwide users on a continuous basis, in all weather, day and night, anywhere on Earth. This requirement is quite realistic today since such GPS devices are advanced, updated, inexpensive, and can provide reasonable precision; GPS provides location information with a precision within a few meters. Location information can be used for directional routing in distributed Ad hoc systems. Research in this area has shown that geographical location information can improve routing performance in Ad hoc networks [33].

Additional care must be taken in a mobile environment because locations may not be accurate by the time the information is used. All protocols based on GPS assume that the nodes know their positions. The Location Aided Routing (LAR) [34], the Distance Routing Effect Algorithm for Mobility (DREAM) [35], and geographical routing [36] are examples of geographic position-assisted routing protocols.

2.4.3 Casting Packets

In this section, the routing algorithms are classified depending on the packet casting type, either unicast or multicast routing protocols, as shown in Figure 2.11.

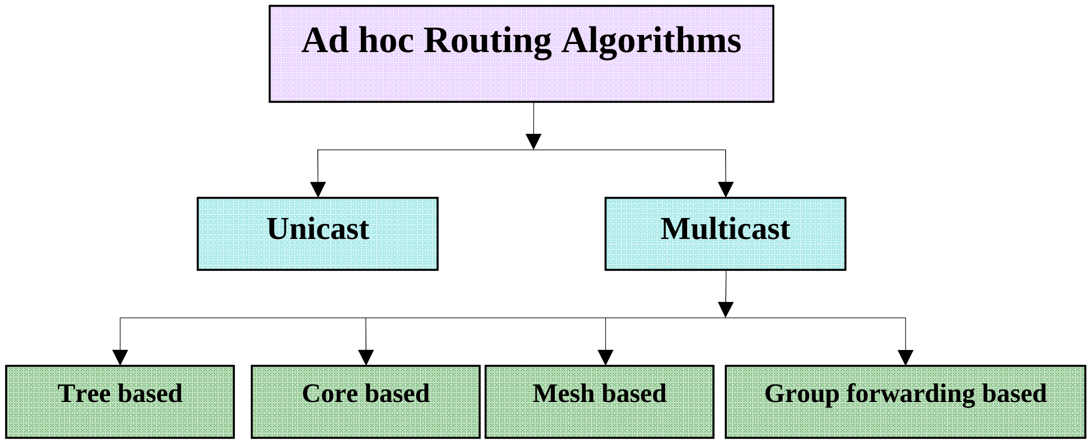


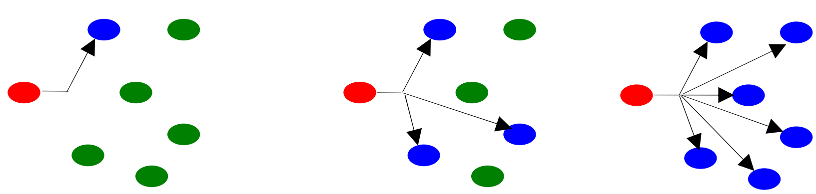
Figure 2.11: Routing algorithm classifications depending on packet casting.

There are three categories to cast the control and/or the data packets in network, as shown in Figure 2.12:

a. *Unicast*: source will send messages to a single destination.

b. *Multicast*: source will send same messages to specific destinations.

c. *Broadcast*: source will send same messages to all possible destinations.



(a) Unicast (b) Multicast (c) Broadcast

Figure 2.12: Packets casting classification.

2.4.3.1 Unicast Routing

Most MANET routing algorithms previously categorized could be classified as unicast routing algorithms such as Optimised Link State Routing (OLSR) protocols [25], Dynamic Source Routing (DSR) protocols [26], and Ad hoc On Demand Distance Vector (AODV) routing protocols [27].

2.4.3.2 Multicast Routing

Many multicast routing schemes have been proposed for wired networks, such as the Multicast Open Shortest Path First (MOSPF) [37] which has been widely used in these networks.

Multicasting in MANET is defined as the transmission of packets to a group of hosts identified by a single destination address. Multicast service is crucial in management applications where one-to-many dissemination is necessary. Applications that include close team collaboration in rescue patrols, military battle, and among scientists with requirements for audio and video communications, are few examples of multicast routing services.

The classification methods for unicast routing algorithms are also appropriate for the existing multicast routing algorithms to be classified into reactive, proactive, and hybrid multicast routing. The Ad hoc Multicast Routing (AMRoute) [38] belongs to the proactive multicast routing category, whereas On Demand Multicast Routing Protocol (ODMRP) [39] is a reactive multicast routing protocol and the Core-based Tree (CBT) [40] is a hybrid multicast routing protocol.

Figure 2.11 shows that the existing MANET multicast routing approaches can be subclassified into tree-based, mesh-based, core-based, and group forwarding-based multicast routing protocols [41]. This subclassification is based on how the distribution paths among group members are constructed. Some of the multicast routing protocols could be included in more than one category, such as the Core-assisted Mesh Protocol (CAMP) [42] which can be characterized as both a core and mesh multicast routing protocol.

a. Tree-based

In tree-based multicast routing protocols, the source nodes are the roots of multicast trees and in them the executing algorithm for distribution tree contraction and maintenance. This requires that a source must know the topology information and address all of its receivers in the multicast group. Therefore, when used for dynamic networks, source-rooted tree-based multicast routing protocols often suffer from control traffic overhead. The AMRoute [37] is an example of one such source-rooted tree-based multicast routing.

b. Core-based

In a core-based multicast routing algorithm, cores are nodes with special functions such as multicast data distribution and membership management. Some core-based multicast routing algorithms also utilise tree structures, but unlike source-rooted tree-based multicast routing, multicast trees are rooted at core nodes. For different core-based multicast routing protocols, core nodes may perform various routing and management functions. For example, in a CBT multicast routing protocol [40], cores are cross points for all traffic flows of multicast groups and may become bottlenecks along the network. On the other hand, in protocols like CAMP [42], core nodes are not necessarily utilised by all routing paths.

c. Mesh-based

In a mesh-based multicast routing protocol, packets are distributed along mesh structures that are a set of interconnected nodes. The mesh structure is more robust than the tree structure for multicast routing in dynamic networks because a mesh provides alternate paths when link failure occurs. However, the cost for maintaining mesh structures is normally higher than that of trees. The ODMRP [39] and CAMP [42] are examples of mesh-based multicast routing protocols.

d. Group Forwarding-based

In the group forwarding-based multicast routing, a set of mobile nodes is dynamically selected as forwarding nodes for a multicast group. Forwarding nodes then assume the responsibility for multicast packet distribution. Using this scheme, it is possible to obtain multiple routing paths and send duplicate messages to receivers through the different paths obtained. ODMRP [39] is a group forwarding-based multicast routing protocol that uses adaptive forwarding groups to accomplish this.

2.4.3.3 Broadcasting Methods

The broadcasting mechanism is used by MANET nodes for periodic messages (control message). A number of research groups have proposed efficient broadcast protocols based on distributed and hierarchical methodologies. The broadcasting methods could be subclassified according to their transmission methodology, as shown in Figure 2.13. In addition to the simple flooding, the subclassification includes probability-based methods, area-based methods, and neighbour knowledge methods. Most existing distributed network-wide broadcast techniques have been summarised and categorized in Reference [43].

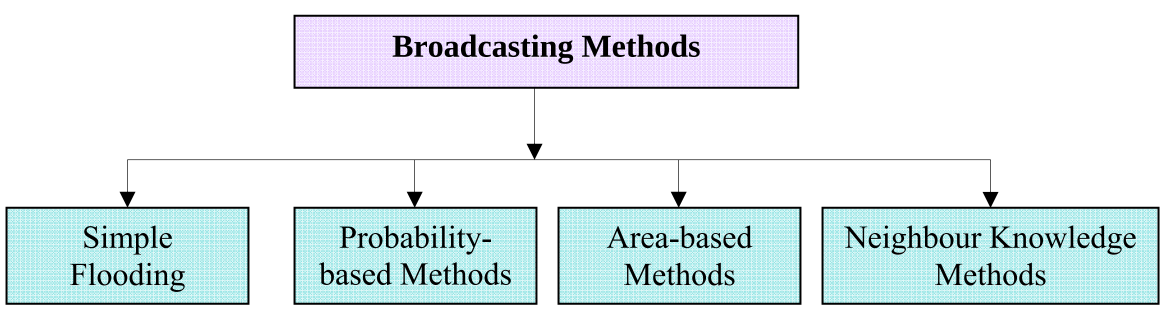


Figure 2.13: Classifications of broadcast methodology.

a. Simple Flooding

Most of the routing protocols use a generally inefficient form of broadcast called simple flooding. In simple flooding, when a node receives a packet to be broadcast for the first time, it transmits the packet to all nodes within its transmission range. In dense networks, the simple flood wastes bandwidth and node resources. DSR [26] and AODV [27] routing protocols use the simple flooding technique.

The following methods improve upon simple flooding and do not require that every node receive a packet to transmit it further.

b. Probability-based Methods

Using the probability-based protocols [44], the node decides whether to rebroadcast according to a specified probability or a simple conditional event which relates to the probability of reaching additional neighbours.

c. Area-based Methods

Area based methods [44] use knowledge of sender node locations to estimate whether a transmission will reach a significant amount of additional coverage area. LAR [34] and DREAM [35] include area-based methods in their routing protocols.

d. Neighbour Knowledge Methods

Neighbour knowledge methods [44] require the use of "Hello"-type packets so that nodes have explicit data regarding their neighbourhood topology; the nodes then use this neighbour data to decide whether to rebroadcast a packet. The OLSR routing protocol [25] implements this method.

2.4.4 Network Routing Metrics

In this thesis, a new classification for routing algorithms has been added which depends on the routing metric. The routing metric used in the identification of the routing path could also be used as a criterion for MANET routing protocols classification, as shown in Figure 2.14.

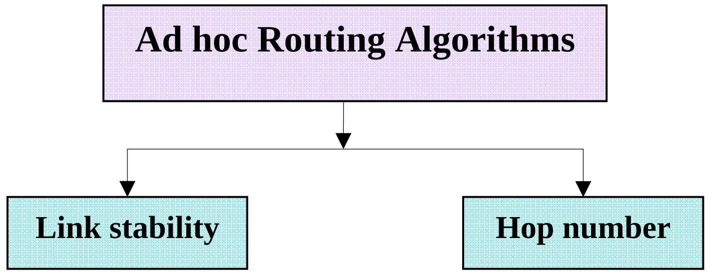


Figure 2.14: Routing protocol classifications depending on route metric.

In the previous sections, all mentioned MANET protocols have based on the hop number as a routing metric, such as in OLSR [25], DSR [26], and AODV [27]. If there are multiple routing paths available, the path selected will be the shortest routing paths with the minimum hop number in order to decrease traffic overhead and reduce packet collisions when compared to longer routing paths.

However, one disadvantage to the mobility in MANET is that it can cause route failure and frequently leads to route discovery. Therefore, the link stability has to be considered in the route construction. Routing approaches such as Associativity-based Routing (ABR) [45] selects routes based only on nodes' link stability, where each node has an associative state that implies the period of stability. ABR is a simple bandwidth-efficient distributed routing protocol that supports mobile computing in a conference-sized MANET environment. Unlike the proactive or reactive routing algorithms, this protocol does not attempt to consistently maintain routing information in every node. In this manner, the routes selected are likely to be long-lived; hence, there is no need to restart frequently, resulting in a higher attainable throughput. Route requests are broadcast on a per need basis. The protocol is free from loops, deadlock, and packet duplicates and has scalable memory requirements.

2.5 Summary

This chapter presented a review of the routing process in MANET, which is much more complex than in wired networks because of the host mobility, interference of wireless signals, and the broadcasting nature of wireless communication. The complexities of this process and the associated issues have motivated researchers to develop several MANET routing protocols, with varying performance under different conditions.

Each routing protocol developed according to a specific criterion. In this chapter, an overview of four different MANET routing protocol categories was presented, including design philosophy, network structure, packets casting, and network routing metric. Each of these categories was used to compare, classify, and group MANET routing protocols with similar characteristics. These characteristics relate mainly to the information utilised for routing that determined the nodes' roles in the routing process. In this chapter, a new type of classification for MANET routing protocols was added based on network routing metrics.

The review in this chapter indicates that the invention of new protocols is not a solution due to the large number of protocols already available. However, there should be an understanding of the network requirements and conditions for which each protocol is suited and will function best. For each of these criteria, there is a wide list of protocols that will meet its needs; therefore, this understanding of requirements and conditions is crucial to selection of the right protocol to enhance efficiency and performance.

As mentioned previously, focusing on a particular characteristic leads to the design of a particular routing protocol. Therefore, a range of comparisons between the routing protocols for each criterion should be made and then evaluated.

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Chapter 3

Optimisation in MANET Routing Protocol

3.1 Introduction

The evolution in mobile applications demands extra attention from the researcher working to optimise MANET for better service. The optimisation in MANET, however, is more difficult than that of wired networks due to MANET characteristics such as lack of centralization, network mobility, and multi-hop communications. Routing optimisation is therefore one of the most important fields in today's MANET development.

The main contribution of this chapter will be to present the optimisation work in MANET routing protocols up to now. Various classifications for the optimised routing protocols have been presented according to the routing metrics, the prediction techniques, or the use of Artificial Intelligence (AI). The chapter then identifies the relationship between the works reviewed and the work within the thesis.

The chapter is organised as follows: Section 3.2 includes an overview of the invented MANET optimised routing protocols based on routing metrics, predictions techniques, and AI techniques; Section 3.3 relates the work in this thesis to other research reviewed in terms of objectives, models, the prediction method, and design; and finally, the conclusion is given in Section 3.4.

3.2 MANET Routing Protocol Optimisation

In MANET, optimisation has been used in different wireless layers and in a variety of techniques. The attention of researchers over the last decade, however, has been focused specifically on enhancing the MANET routing protocols. The principle behind optimizing MANET route is to control the flows in the network such that the flows are given better or best-effort treatment. Therefore, the best metrics to represent the success of the optimisation process and also measure MANET performance could be increased throughput, reduced packet loss, reduced latency, and reduced load. As such, the literature tends to focus on throughput and delay as the two most important performance metrics for optimisation solutions.

3.2.1 Optimum Routing Protocols Based on Routing Metrics

In the literature, most of the optimise protocols, as in [1], are designed based on traditional or widely implemented protocols. These optimised protocols have been enhanced from the original routing protocols by including some features that perform the optimisation. This process converts the traditional routing protocols to an optimise protocol.

MANET optimisation has been based on routing metrics, such as the traditional hop count metric, and the context-aware metrics, as discussed below.

3.2.1.1 Hop Count Metric

Selecting the optimum path (that with the least cost) according to the hop count metric is one way of optimizing the route. The optimum route relaying on the minimum hop count could be accomplished in different ways, such as: by selecting the shortest path (node by node), as in Al-Khwildi and Al-Raweshidy [2]; by selecting one of many paths discovered through the route discovery process, as in Dai and Wu [3]; or by a unicast query in the route discovery process, as in Seet et al. [4].

3.2.1.2 Context-Aware Metrics

In Ad hoc networks, routing not only has to be fast and efficient, but also adaptive to the changes in the network topology; otherwise, the performance may be severely degraded. As mentioned before, route optimisation can be accomplished by considering those context-aware metrics which measure MANET performance. Context-aware metrics could include mobility awareness, energy awareness, power awareness, availability, contention awareness, and congestion awareness. Research to find more context-aware metrics that affect the routing process is ongoing. Including such metrics in the invented protocols should help to improve MANET performance.

Examples of those context-aware metric(s) that researchers depend upon to create their optimised protocol are listed below:

1. The *energy-aware* metric was represented by two objectives; node's life time and the overall transmission power were the basis for creating the battery-life aware routing schemes for wireless Ad hoc

networks in [5]. In that development, the aim was to minimize the overall transmission power requested for each connection and to maximize the lifetime of Ad hoc wireless networks, meaning that the power consumption rate of each mobile host must be evenly distributed.

The routing schemes invented by Kim et al. [6] also relied on an energy aware context metric to select the path of least cost and sufficient resources.

Furthermore, in the Mukherjee et al. paper [7] the energy aware metric was the major element in developing an analytical optimised method to minimize routing energy overhead.

In the multicast routing field, Moh et al. [8] invented a robust two-tree multicast protocol also based on the energy aware context. This protocol uses two trees, a primary and an alternative backup tree, to improve the energy efficiency and to offer a better energy balance and packet delivery ratio.

2. The *bandwidth-aware* metric was utilised to create the Mukhija and Bose [9] Reactive Routing Protocol.

3. The *congestion-aware* metric was utilised in the Lu et al. paper [10] to establish distance vector routing protocol.

In addition, more than one context-aware metric was combined with the routing metric to achieve a better outcome. Reference [11] introduced the *availability aware* metric that is represented by the quantity relationship of *link status* and *mobility aware*, as the quantity is required to predict the link status for a future time period in consideration of mobility.

Next*, path congestion* and *energy usage* metrics were combined with the *hop count* metric in the Cao and Dahlberg protocol [12] to represent the cost criteria that defines path cost during *Route discovery*.

Moreover, the routing schemes developed by Chen and Nahrstedt [13] select the network path with the least cost and sufficient resources to satisfy a certain delay and bandwidth requirement in a dynamic mobile environment. This protocol combines *hop count* with *energy, latency, and bandwidth-aware* metrics.

Additionally*, energy-aware* and *congestion-aware* metrics were both included in the mobile routing approach of Ivascu et al. [14].

Usually, the ZRP is configured for a particular network through an adjustment of a single parameter: the routing zone radius. Paper [15] combines *mobility-, contention-,* and *congestion-aware* metrics to address the issue of configuring the ZRP and providing the best performance for a particular network, at any time.

This paper also adds more parameters that affect the performance of the ZRP, including relative node velocity, node density, network span, and user data activity.

Finally, other combinations were also possible, such as *power-aware* and *mobility-aware* metrics for mobile Personal Area Network in Park et al. [16]. This optimisation technique includes context-aware metrics with routing metrics that would be effective when activated or employed in an online or real scenario.

3.2.2 Optimum Routing Protocols Based on Prediction

While the previous optimisation technique based on routing metrics can be considered as one type of optimizing, another optimisation type is the predication technique. Optimising routing metrics based on prediction is utilised in networking to achieve a better outcome. Prediction yields an initial idea about the behaviour of network elements. In the study by Jiang et al. [17], an equation was formulated to predict the link status for a time period in the future for a *mobility aware* quantity, whereas Ghosh et al. [18] predicted the user movement based on GPS receivers to control a hub-based orbital pattern in the Sociological Orbit aware Location Approximation and Routing (SOLAR) protocol.

3.2.3 Optimum Routing Protocols Based on Modelling /Prediction Techniques

Modelling is another optimisation technique which is also included in the literature. The modelling process in MANET is utilised to support the prediction technique, as it includes the estimation of various performance metrics for the multi-hop wireless networks; for example, the empirical model in [19] developed to characterize the relationship between the proposed response indexes, according to influential factors. The four response indexes were packet delivery ratio, end-to-end delay, routing overhead, and jitter. The influential factors were node mobility, offered load, network size, and routing protocol.

A mathematical framework to model *contention* was presented by Jindal and Psounis [20]. This framework was used to analyse *any* routing scheme, with *any* mobility and channel model. This framework can also compute the expected delays for different representative mobility-assisted routing schemes under random direction, random waypoint, and community-based mobility models. This framework could be considered *mobility model aware* as it investigated three different mobility models [21] to conclude the delay. The delay expressions were then used to optimise the design of routing schemes.

Additionally, in the bi-objective linear programming mathematical area, Guerriero et al. [22] proposed a bacterium optimisation model which allows the *energy* consumption and the *link stability* of mobile nodes to be taken into account, simultaneously.

Prediction based on modelling is an interesting area in optimisation. This technique was employed by Nogueira et al. [23] to create a framework to model MANET. The framework integrates important functional characteristics such as traffic flow, mobility, and background traffic, with each characteristic represented by its own matrix. The mathematical network model was built from a set of (past) traffic measurements and the corresponding network performance metrics. This constructed model can then be used to predict future values of the network metrics, depending on the mathematical cost function, and based only on the network gateway's traffic measurements parameters.

3.2.4 Optimum Routing Protocols Based on Application Requirements

Prediction based on MANET application requirements is a very important issue that could be considered as another type of optimisation in MANET. The Cross-layer Route Discovery Framework (CRDF) [24] proposes Routing Strategy Automation (RoSAuto) technique that enables wherein each source node automatically decides the routing strategy based on the application requirements, and then each intermediate node further adapts the routing strategy so that the network resource usage can be optimised. In addition, CRDF was designed to provide a flexible architecture for searching desirable routes with low control overhead. CRDF relies on the Priority-based Route Discovery Strategy (PRDS) mechanism to solve the "next-hop racing" problem and the "rebroadcast redundancy" problem.

3.2.5 Optimum Routing Protocols Based on Programmable Framework

Prediction based on a programmable platform is another type of optimisation in MANET. Papers [25], [26], and [27] present a context-based programmable framework and functionality for dynamic service/protocol deployment. This technique allows the nodes of a MANET to download and safely activate the required service/protocol software dynamically. According to the available contextual information, the nodes will evaluate the preconditions that will trigger the downloading and activation. This strategy leads to the arrangement of the nodes' capabilities so that common services and protocols can be deployed even if the downloading and activation are not available at every node. In addition, dynamic context-driven deployment may lead to a degree of network self-optimisation.

3.2.6 Optimum Routing Protocols Based on Artificial Intelligence

Evolving Artificial Intelligence (AI) has played a key role in optimisation. There are a variety of optimisation techniques to solve MANET routing problems in AI standard repertoire, examples of which are given below.

3.2.6.1 Neural Network Approach

Guo and Malakooti [28] present a solution for optimizing the route through employing intelligent use of the nodes' past experiences of the network traffic conditions in order to make predictions for future network traffic conditions based on these experiences. Furthermore, Guo and Malakooti developed a neural network to predict the mean per-packet one-hop delays. The nodes then used the predicted one-hop delays to participate in dissemination of routing information.

3.2.6.2 Neuro-Fuzzy Approach

Martinez-Alfaro and Hernandez-Vazquez [29] used an Adaptive Neuro-fuzzy Inference System (ANFIS) as a predictor. ANFIS is employed inside an Ad hoc hierarchical network to resolve the route error optimisation problem. The principal problem to resolve was how many nodes the routing protocol can accept? Given that, the larger the network size, the more performance will suffer. In this Ad hoc hierarchical network, ANFIS predicts future node mobility to keep the network working at the same level irrespective of how many nodes join the network.

3.2.6.3 Swarm Intelligence Approach

Many routing protocols draw inspiration from Swarm Intelligence similar to the ant colony adaptive routing algorithm of Caro et al. [30]. In their study, the authors presented the algorithm as a robust, decentralized, and self-organised method of routing.

Moreover, Huang et al. [31] investigated a multicast routing protocol which strived to meet the variation of network topology behaviour (scalability), and satisfy the requirements of specific multimedia traffic, utilising Particle Swam Optimisation (PSO) in volatile MANET environments.

In the sensors network, Shih [32] evolved PSO to create an *energy aware* cluster-based routing protocol that exploits the geographical location information of nodes to assist in network clustering. Also, in the same Ad hoc sensor network area based on Swarm Intelligence, a robust *mobility aware* and *energy aware*

SIMPLE routing protocol [33] was the solution suggested by Yang et al. for the data acquisition problem found in those networks with mobile sinks.

Furthermore, Rajagopalan and Shen [34] used the Swarm Intelligence mechanisms in Ad hoc networking with Swarm Intelligence (ANSI) to produce a *congestion aware* ANSI routing protocol to select next-hops for both pure and hybrid Ad Hoc networks.

Finally, based on the Swarm Intelligence mechanism, Shen and Rajagopalan [35] created an adaptive Protocol-Independent Packet Delivery Improvement Service (PIDIS) mechanism to recover lost multicast packets. The advantage of this mechanism is that the operations of PIDIS do not rely on any underlying routing protocol and can be incorporated into any Ad hoc multicast routing protocol.

3.3 Related Work

This section will compare the surveyed works with the work proposed in this thesis, namely the Intelligent-MANET (I-MAN) routing protocols optimisation system. The comparison elements are models, prediction, objective, and design.

3.3.1 Models

As seen previously, a mathematical equation was utilised in MANET to create models such as those of Jindal and Psounis [20], Guerriero et al. [22], and Nogueira et al. [23]. Also relevant is an attempt by Martinez-Alfaro and Hernandez-Vazquez [29] to utilise AI modelling techniques to solve MANET routing problems. Although there is a similarity between the work in [23] and the thesis in that both investigations create MANET models, the work in [23] creates mathematical models, whereas the models for the I-MAN system are created by deploying AI (that's mean, by implementing neuro-fuzzy (NF) technique).

The work in [20] and [22] have created models for parameters in the network, whereas the I-MAN 3D models in this thesis represent the network performance against context parameters. To our knowledge, there has been no previous MANET modelling done in this format before.

3.3.2 Prediction

Both work, in [23] and this thesis utilised prediction components for optimisation. The work in [23] relies on mathematical equations whereas the I-MAN routing protocols optimisation system utilises AI by implementing Particle Swarm Optimisation.

3.3.3 Design

The main difference between most of the mentioned works and the work in this thesis is that previous researchers are proposing new protocols to be added to the numerous existing routing protocols, as each protocol is only useful in a certain network context. However, the I-MAN optimisation system proposes no new protocol; it is a selection approach that deploys the available routing protocols to their best advantage.

Second, the work in [20] and [35] on the invented model or mechanism could be applied with any network routing protocol. Both researches are relevant to the re-tuned system in that they are flexible and can be adapted to changes.

The Programmable Ad Hoc network (PAN) project [27] shares with the I-MAN optimisation system the basic design idea to select routing protocol depending on contextual information. Nonetheless, the two approaches differ in several fundamental ways:

1. The PAN project considers network programmability whereas the I-MAN system considers optimisation techniques to solve MANET routing problems.

2. The PAN project creates context models utilising lightweight Unified Modeling Language (UML) whereas the I-MAN system creates AI models utilising neuro-fuzzy.

3. The PAN project models represent the network context alone whereas the I-MAN system 3D models represent the network performance according to the network context (the network history).

4. The hierarchal network of the PAN project consists of three layers, manger head, cluster head, and cluster node, whereas the I-MAN system network consists two layers, Intelligent node (cluster head) and network node (cluster node).

5. Although the PAN project and I-MAN system are both *mobility aware* and *scalability aware*, these parameters were implemented in different ways. For the PAN project, the scalability problem is solved by changing the network topology to a hierarchal approach that consists of three layers so that as the number

of nodes increases, more clusters are added; the I-MAN system, on the other hand, included the scalability (network size) as the second context parameter.

6. Finally, the work presented in the PAN project was time discrete; there was no graph presenting one continuous experimental (or simulation) scenario to show the switching of the invented scheme through time or which routing protocol (AODV or OLSR) was adopted for each period. Also, the cluster nodes switching adaptation strategy was not clear.

3.3.4 Objective

Most of the previous protocols surveyed have focused on individually improving the number of network performance parameters and having multiple objectives, except for the work undertaken in paper [19] and the system in this thesis. The I-MAN approach is significant in that it can better represent a single objective by combining the network performance parameters in one equation.

3.4 Summary

Creating the optimised routing protocol in MANET was first represented by the protocol that selects the shortest path. Later, context-aware metrics were considered to develop and optimise the routing protocols. Prediction, modelling, and AI techniques were also included to support the optimisation.

Researchers have invented optimum routing protocols with the main goal of their design formulated for particular objectives in the invented protocol. As such, there are already many routing protocols that equate the most suitable path with the shortest, most reliable, or most self-organised path. Also, there are the self-management protocols that are composed of self-protecting, self-healing, self-configuring, and self-optimizing components. Although they have different objectives, each of these protocols reflects their objective.

For this reason, the search for the most effective routing protocol that provides the optimum path and satisfies the entirety of objectives still continues, as to our knowledge no routing protocol can handle and solve all these objectives at once, although there are many protocols which can solve one, two, or maybe even three of these objectives. Thus, from the survey undertaken in this chapter, it can be concluded that there is a need for an approach that could deploy the existing algorithms based on the network's needs.

3.5 References

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Chapter 4

I-MAN Design

4.1 Introduction

Wireless networks are designed to provide service to their users at an acceptable level; performance modelling and evaluation should therefore play a crucial part in the designing and monitoring of those processes which ensure the successful deployment of a network. As such, network traffic and characteristics should be analysed and properly controlled to achieve the desired service. Reaching this design stage in MANET demands specific modelling and design tools.

Therefore, in this thesis the aim has been to design an intelligent system employing Soft Computing [1] to fulfil the above requirement. The goal of Soft Computing is to construct a new generation of Artificial Intelligence, known as *Computational Intelligence*, to develop intelligent machines and to solve non-linear and mathematically un-modelled system problems. Soft Computing, as such is ultimately a method of modelling. With this method, an intelligent system could be created by combining intelligent techniques such as fuzzy logic, neuro-computing, and evolutionary, genetic, and probabilistic computing into one multidisciplinary system. As a result, the intelligent system should have the ability to learn from those experiences that will lead to an achievement of the system objectives. In other words, it senses its environment and learns the correct action for each situation [2].

In this chapter, the Soft Computing goal has been achieved through considering Artificial Intelligence (AI) techniques and merging them into one system, as the AI system could be a program that has inputs and learns which outputs get the most approval, either by human beings or a program that can contain the inputs from the system previous knowledge.

This chapter also outlines the components needed to design an intelligent optimised system, and presents three routing protocols for study and comparison. The main contribution is the novel design of the Intelligent-Mobile Ad hoc Network (I-MAN) routing protocols optimisation system.

The remainder of the chapter is organised as follows: in Section 4.2, the I-MAN routing protocols optimisation system design elements are presented and explained in detail; in Section 4.3, the three selected routing protocols implemented with the proposed design (the intelligent optimisation system) are described; with particular focus on the routing protocols' weaknesses, strengths, and a comparison between the three protocols; and finally, Section 4.4 includes a chapter summary and findings.

4.2 I-MAN Design Elements

The proposed intelligent system requires contributions from multiple fields, as each field output will contribute to the proceeding field to create the final intelligent system. The first field is the communication field, the second is the modelling field, and the third is the optimisation field. The first field is represented by a wireless MANET whereas the second and the third fields are AI.

The proposed intelligent system objective is to select the optimum routing protocol for MANET, in that particular context. Therefore, designing the I-MAN routing protocols optimisation system demands specific simulation, modelling, and optimisation tools. Moreover, different techniques for modelling and monitoring should be tested in order to create the finest system. Hence, four main components should be employed, these being the Simulator, Modeller, Optimiser and protocol Switcher (in which the MANET network will cooperate with the intelligent system to achieve its objective), in conjunction with one another to accomplish the proposed system's design,

Given below is a brief list of definitions for all elements needed to create the I-MAN routing protocols optimisation system.

A. ***Simulation*****:** simulates MANET in different scenarios containing different contexts, collects the performance metrics, and then determines the representative value for each performance metric.

B. ***Modelling*****:** utilises modelling techniques to generate MANET performance models for each routing protocol depending on entire scenarios.

C. ***Optimisation*****:** utilises optimisation techniques to optimise MANET performance based on the performance models by suggesting the optimum routing protocol for the current context.

D. ***Switching protocols:*** implements the switching technique between the protocols in MANET and maintains all the data needing to be transmitted before the switching process in the network.

Figure 4.1 shows the I-MAN routing protocols optimisation system block diagram and the four aforementioned components. Further explanation of how each component in the I-MAN routing protocols optimisation system block operates will be given and discussed in detail in the following chapters. Chapter 5 defines the Simulator settings and presents its results; Chapter 6 defines, investigates, and compares the modelling methods; Chapter 7 defines, investigates, and compares the optimisation techniques employed; and Chapter 8 explains the modification in the normal wireless node to adopt the protocol switching technique. This chapter also presents the embedding process for the Modeller and the Optimiser in the normal wireless node.

The I-MAN routing protocols optimisation system compares and evaluates the protocols and then finds the best protocol for that context. This proposed system utilised the original and widely implemented protocols in a similar manner as past researches [3]. The intelligent system includes a list of the evaluated routing protocols, as more routing protocols could be added or unwanted routing protocols removed from this list. Each protocol evaluated depended on network performance while the network is operating with a routing protocol.

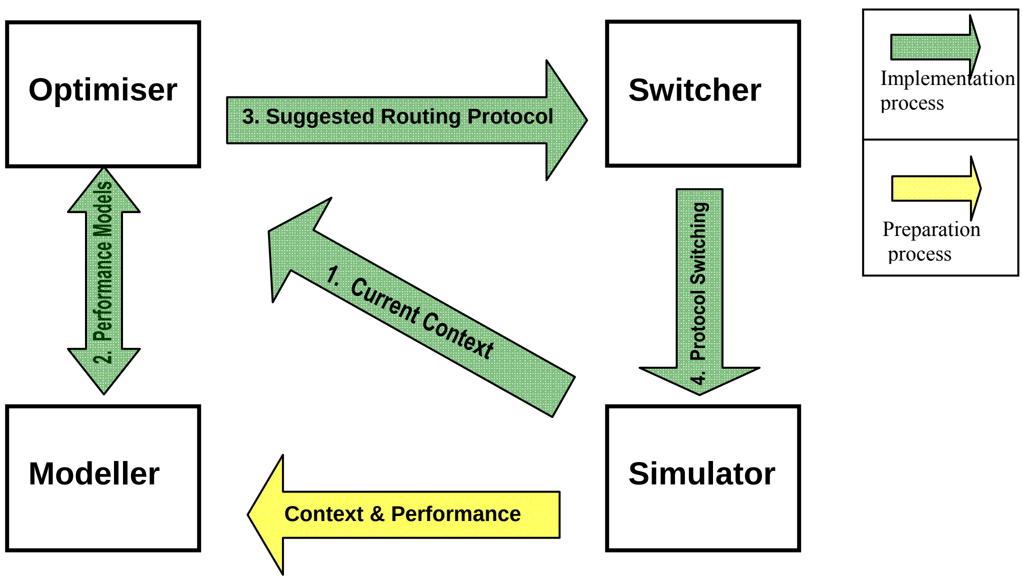


Figure 4.1: I-MAN routing protocols optimisation system block diagram.

The arrows in Figure 4.1 represent the system's task sequences. The yellow arrow represents the preparation stage, whereas the green arrows represent the case study and implementation process. After the Simulator finishes its task, its output (represented by the yellow arrow) will be the required input data for the Modeller.

The system implementation will start from the first green arrow, the current context; will be passed to the Optimiser. All solutions generated by the Optimiser will then be passed to the Modeller to predict the network performance for each protocol. The performance metrics will then be calculated and passed to the Optimiser to select the optimum protocol. The decision to switch to the optimum protocol will then be passed to the nodes, combined with the threshold time at which the entirety of network nodes will adopt and operate with this protocol.

The Modeller block represents the models for the previous network performance history. The more data collected for each model, the more accurate the performance Optimiser's decision will be. After building the models for the network performance, the models will act as the Optimiser's reference. The Optimiser will refer to the models before its decision.

The flowchart shown in Figure 4.2 lists the intelligent system tasks based on a time scale. The first preparation procedure simulates the MANET operation with various routing protocols through different network contexts, then collects and sorts MANET performance parameters. The following procedure generates the MANET performance models for each operating routing protocol. Then, creating the intelligent system (that contains the models aforementioned), the system will be activated when it receives the current MANET context. Next, the system will determine the optimum routing protocol after optimizing and calculating the network performance as the network operates with each protocol. The Optimiser optimum protocol will be checked with the routing protocol on operation. If both routing protocols are the same, then no switching order will be send to the nodes; however, if the protocol is different, then a switching order will be sent to all the network nodes to switch to the new routing protocol. This process will be repeated until the simulation is completed.

This intelligent system is responding to the network dynamic changes by continuously updating with the network context to decide the optimum routing protocol for that period. This means that the network could benefit from more than one routing protocol throughout the simulation period. Finally, the Optimiser decision does not rely on a *single* objective, but on an equation. This equation should include the performance parameters (objectives) that will help in choosing the optimum routing protocol.

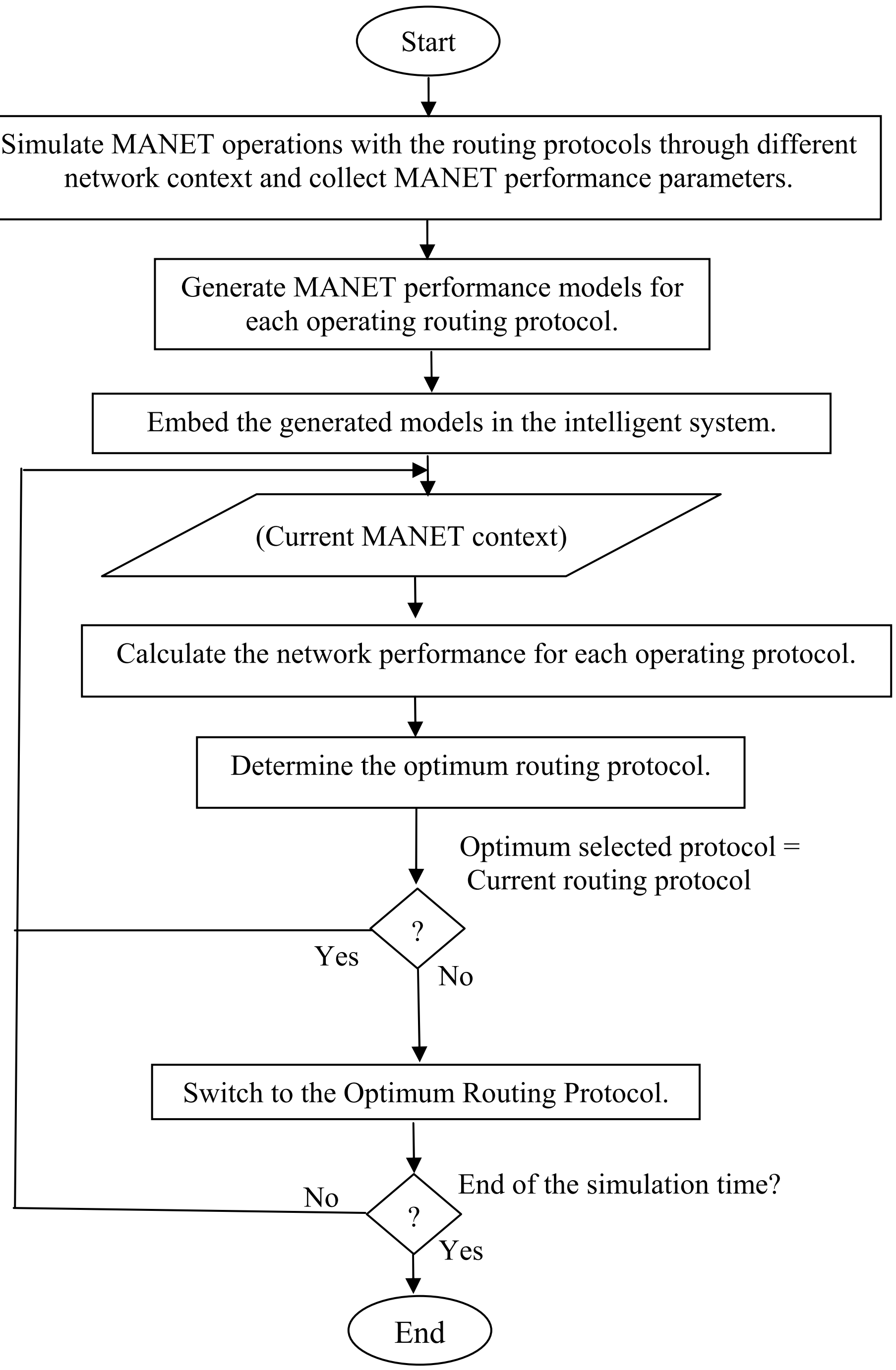


Figure 4.2: Flowchart for the I-MAN routing protocols optimisation system design.

4.3 MANET Routing Protocol Techniques

This section contains a description of the MANET routing protocols implemented and evaluated in this thesis. Three well known and widely implemented routing protocols have been selected for review, the Optimised Link State Routing (OLSR), Dynamic Source Routing (DSR), and Ad hoc On Demand Distance Vector (AODV) routing protocols, and are discussed below.

4.3.1 OLSR Routing Protocol

The Optimised Link State Routing (OLSR) protocol [4] is a Table-Driven protocol based on the traditional Link State algorithm (mentioned in Chapter 2). The point-to-point OLSR routing protocol is a non-uniform proactive protocol. Under the OLSR routing protocol strategy, nodes in the network exchange periodical topology information with each other and select a set of neighbouring nodes called *MultiPoint Relays (MPRs)* to retransmit their packets. This technique minimizes the size of control messages and the number of rebroadcast nodes during a route update.

To explain the producer of selecting *MPRs* [5], Figure 4.3 illustrates how node A selects its *MPR* set. Periodic *Hello* messages will be broadcasted from node A to all immediate neighbours to swap neighbour lists and calculate the *MPR* set. Node A deduces from neighbour lists the nodes that are two hops away and computes the minimum set (*MPR* set) of one hop relay points vital to reach the two-hop neighbours. For example, in Figure 4.3, node A selects nodes E, F, and G to be the *MPR* set. Since the nodes selected cover all the nodes that are two hops away. Each node notifies its neighbours about its *MPR* set in the *Hello* message. After receiving the *Hello* message, each node records the selected nodes and calls them *MPR selectors*. The frequency of link state updates is adjusted depending on the changes detected in the *MPR* set. With a stable *MPR* set, the period is increased until it reaches a refresh interval value, whereas with a changing *MPR* set, the period of link state exchange is set to a minimum value.

Through link state messages, each node obtains network topology information and constructs its routing table. Routes used in OLSR only include *MPRs* as intermediate nodes, whereas each node determines, in terms of hops, an optimal route to every known destination using its topology information (from the topology table and neighbouring table), and stores this information in a routing table. Therefore, routes to every destination are immediately available when data transmission begins. Any node which is not *MPR* can read and process each packet, but cannot retransmit.

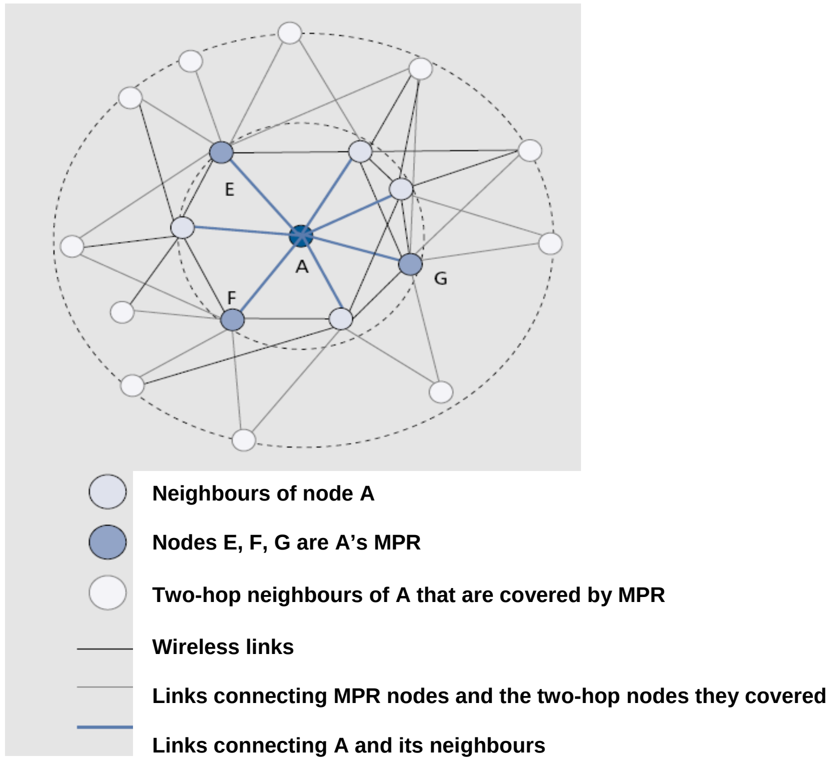
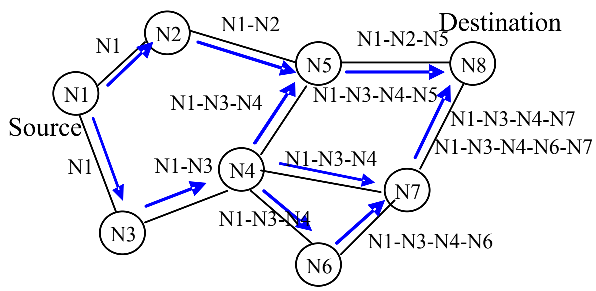


Figure 4.3: An illustration of *MPR* nodes in the OLSR routing protocol [5].

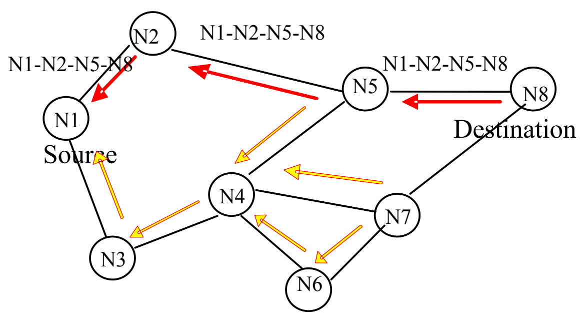
4.3.2 DSR Routing Protocol Technique

The Dynamic Source Routing (DSR) protocol [6] is a simple On Demand routing protocol for the purposes of source routing. A reactive routing protocol, DSR allows senders to control the routes used in routing their packets and also allows multiple routes to any destination. All packets that are sent using DSR protocol contain the complete list of nodes which the packet will traverse. Each node should maintain a *route cache* that includes all known source routes. The route cache will be continually updated as new routes are learned. When the source's packets must be sending to some destination, the source first checks its route cache. If it has an unexpired route to the destination, it will utilise this route to send the packet, but if the node does not have such a route, it initiates the *Route discovery* procedure mentioned in Chapter 2. As shown in Figure 4.4 (a), the source node broadcasts during *Route discovery* process a *route request* packet with a unique identification number. The *route request* packet encloses the addresses of the destination and the source nodes. The node that is not the destination node or does not see the same *route request* packet as before will attach its IP address to the *route request* packet and rebroadcast the packet.

The IP Time To Live (*TTL*) field will be incremented in each *Route discovery* in order to control the distribution of the *route request* packets. The *route request* packets continue to spread until they reach the destination node or any other node that has a route to the destination node [7].



(a) Building of the route record during route discovery



(b) Propagation of the route reply with the route record

Figure 4.4: Formation of *Route discovery* in DSR.

As shown in Figure 4.4 (b), the destination node responds to the incoming *route request* packets and creates a *route reply* packet that encloses the list of nodes which the *route request* packet has traversed. Then, based on a minimal hop count or latency, the source node may select one or more *route reply* packets for a single target node.

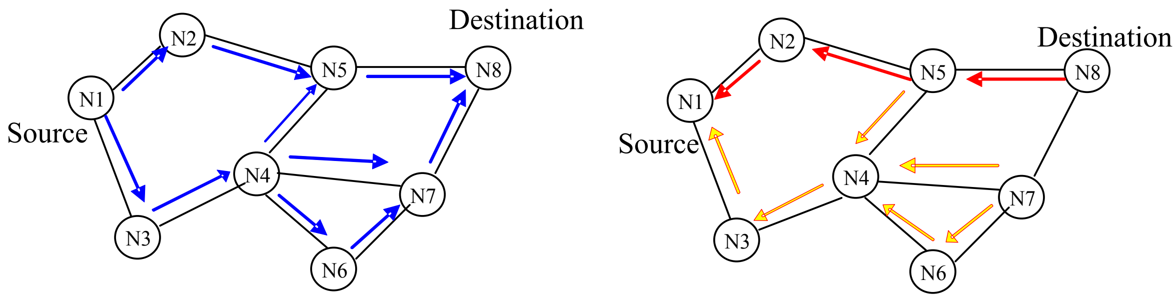
The DSR *Maintenance* mechanism consists of the *route error* packets and the acknowledgments. When the data link is broken, the node generates these *route error* packets. Each node that receives a *route error* packet removes the hop in error from its route cache and shortens all routes contained by that hop at the breaking point. In addition to *route error* messages, the acknowledgments from where the node can hear the next hop forwarding the packet along the route are useful to verify the correct operation of the route links [8].

4.3.3 AODV Routing Protocol Technique

The Ad hoc On Demand Distance Vector (AODV) Routing Protocol [9] is a reactive routing protocol previously mentioned in Chapter 2. AODV borrows the basic *Route discovery* and the *Maintenance* mechanisms from the DSR protocol, whereas AODV borrows the periodic beaconing and the sequence numbering (the hop-to-hop routing vectors) from the Destination Sequenced Distance Vector (DSDV) routing protocol [10]. Therefore, the On Demand routing protocol AODV is an optimised distance vector routing protocol which finds the routes only when required. Also, AODV employs extensively the sequence numbers in control packets to avoid the problem of routing loops (as explained in the next section). The AODV protocol is advantageous in that it offers quick adaptation to dynamic link conditions, low processing, low memory overhead, and low network utilization.

When a source node starts *Route discovery* to a destination that is not included in its routing table, the source node broadcasts a *route request* packet [11], as shown in Figure 4.5 (a). Each *route request* packet does contain the following: the ID field that represents a unique identification for the *route request* packet, the IP addresses for the source node, the IP addresses for the destination node, the destination sequence number that specifies the freshness of the control packets, the hop count that maintains the number of nodes between the source and the destination, and finally, the control flags. The *route request* starts with a small *TTL* value that increases in following *route requests* when the destination is not found. Each recipient of the *route request* packet that has not know the destination IP address or does not maintain a fresher route to the destination (in another words, does not maintain larger destination sequence number), rebroadcasts the same packet after monotonically incrementing the hop count. If additional copies of the same *route request* are later received, these packets are discarded to reduce overhead. Such intermediate nodes also create and preserve a *reverse route* to the source node for a certain interval of time.

When the *route request* packet reaches the destination node or any node that has a fresher route to the destination, a *route reply* packet, as shown in Figure 4.5 (b), is generated and unicast-travelled back to the source of the *route request* packet. Each *route reply* packet contains the destination sequence number, the IP addresses of the source and the destination, the route lifetime, the hop count, and the control flags. This guarantees that the route path is being set up bidirectionally. Each intermediate node that receives the *route reply* packet, establishes a forward route to the source's packet, and transmits the packet in it. In cases where a node receives a new route (by a *route request* or by a *route reply*) and it has already a route 'as fresh' as the received one, the shortest route will be the one updated.



(a) Propagation of *route request* (b) Path of *route reply* to the source

Figure 4.5: AODV *Route discovery*.

For the *Maintenance* mechanism, each node makes use of periodic *Hello* messages when it needs to detect link breakages on nodes that it considers as its immediate neighbours. In the case that a link break is detected for the next hop of an active route, a *route error* message is sent to its active neighbours using that particular route. Therefore, the mutable information included in the *route error* message is the list of unreachable destinations and their counterparts.

4.3.4 OLSR, DSR, and AODV Loop-Free Technique

The loop problem can be clarified through the following scenario. Assume an existing route link between A and D, as shown in Figure 4.6; next, the link between S and D, which A is not aware of breaks. For example, *route error* message sent by S is lost. Now, assume A wants to send packet to D. It then performs a *route request* that can be replied to via path (S-C-A). Node A will reply since it knows a route to D via node B. This would result in a loop (S-C-A-B-S).

For routing protocols OLSR [4] and AODV [8], an incremental sequence number will avoid the two protocols having the loops problem in their routing mechanism. Implementing the sequence number technique in the previous example, the presence of the sequence numbers will let S discover that the routing information from A is outdated. Node S increments the sequence number when it discovers that link S-D is broken. In this way, the new sequence number will be greater than the one stored by A.

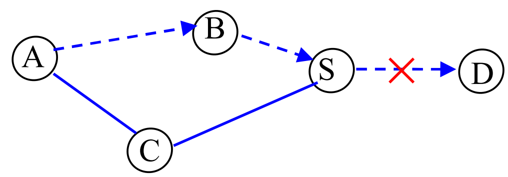


Figure 4.6: Loop technique.

On the other hand, DSR [6] provides loop-free routing by requiring path information. DSR establishes a loop-free route to a destination by carrying the path traversed in *route request* packets and having the reverse path piggy-back on (*route reply*) packets to lead the way to the source, as shown in Figure 4.4 (a and b). However, given a link failure, reliable error updates must be sent to the source, so that a new route can be searched.

4.3.5 Comparison of OLSR, DSR, and AODV Routing Protocols

In this section the main strengths and weaknesses of the three routing protocols, OLSR, DSR, and AODV, have been reviewed. The protocols were evaluated based on the techniques each one used, and their respective operation conditions.

4.3.5.1 Strengths of OLSR, DSR, and AODV Routing Protocols

Here are some major points that delineate the strengths of each technique and define the best operation areas for each protocol:

a. OLSR Strengths

➢ OLSR is suited particularly to dense networks. This means that OLSR is not for use in sparse networks, as all node neighbours become *MPR* nodes. In this case, the OLSR becomes a pure Link State protocol and must operate as the original Link State algorithm, such that each node propagates its link state information to all other nodes in the network [12].

➢ Using the *MPR* technique minimizes the number of control messages and reduces the message flooding overhead. OLSR, furthermore, reduces the number of nodes rebroadcasting link state information (updates). In this way, when a node broadcasts a message, all its neighbours will receive the message and only the *MPR* sets will have to forward the link state information [13].

b. DSR Strengths

- The DSR protocol offers an acceptable performance and overhead in networks of small to moderate size. For large networks, however, there will be longer source-destination paths (long route cache in each node) and an increase in the source path route that piggy-backs on each packet travelling to its destination [6].

- DSR technique nodes can store multiple routes to destinations in their route cache, which means that there is no need for initiating *Route discovery* after a breakage if the source node finds a valid route to the same destination in its route cache [6].

- DSR has a satisfying delay since the nodes can store multiple routes in their route cache. The network nodes delay is the time required to search the node cache for a route before forwarding any data packets. This is very beneficial in a network with low mobility [14].

- DSR does not require any periodic beaconing, or Hello message exchanges. Therefore, nodes can enter sleep mode to conserve their power and bandwidth [15].

c. AODV Strengths

- AODV has two important features which allow the protocol to be adaptable to highly dynamic networks. First, AODV adopts the destination sequence number technique used by the Destination Sequenced Distance Vector (DSDV) in an On Demand way. Destination sequence numbers are important to ensure loop-free and up-to-date routes. Second, AODV maintains in each node a base time state regarding the utilization of the individual routing table entries, whereas routing table entries will expire if not recently used [14].

- AODV also reduces the flooding overhead. This occurs because AODV routing information is maintained in the node's next-hop routing tables containing the destinations for which the node currently has a route. A routing table entry expires if it has not been used or reactivated for a pre-specified expiration time. Therefore, the node has only to maintain the routing information about the active paths. The path, then, will be the result of exchanging the portions of the routing table necessary for establishing the route [16].

- AODV has potentially less routing overheads than DSR, as AODV packets only carry the destination address (A *route request* packet is small in size because it does not contain information about the whole route path), unlike DSR packets which carry an array of addresses [17].

- A node operating AODV MAY offers connectivity information by broadcasting local Hello messages. A node should only use Hello messages if it is part of an active route. AODV does not require any periodic beaconing for inactive nodes. Therefore, the inactive nodes can enter sleep mode to conserve their power and save a considerable amount of bandwidth in the network [18].

4.3.5.2 Weaknesses of OLSR, DSR, and AODV Routing Protocols

This subsection points out the weaknesses of the three routing protocols, as described below:

a. OLSR Weaknesses

- OLSR is a Table-Driven protocol that requires periodic beaconing (*Hello* message exchanges) to update the network information [15]. These messages will produce an overhead and load the network. The load will increase if the number of nodes in the network increases. The OLSR routing protocol is unlike On Demand routing protocols: DSR or AODV, which do not depend on the periodic beaconing in *Route discovery* techniques. This also means that OLSR overhead will grow in a network with high mobility because of the protocol's frequent topology table update.

b. DSR Weaknesses

- DSR is not appropriate for a large network as the overhead may consume most of the bandwidth [19]. DSR uses source routing that demands every packet should carry the full path address for every hop in the route from the source to the destination. This means DSR will not be very effective in large networks as the amount of the path carried in the packet will continue to increase when the network diameter increases. Also, DSR route replies carry the address of every node along the route [15].

c. AODV Weaknesses

- Nodes operating AODV routing protocol may experience large delays during route construction. Like any On Demand routing protocols, AODV need to establish *Route discovery* between source and destination before sending the data packets. Also, if the link failure accrues, *Route discovery* should be initiated, which involves extra delays and bandwidth consumption specially when the size of the network increases [20].

4.3.5.3 Characteristics of OLSR, DSR, and AODV Routing Protocols

Table 4.1 characterizes each of the three protocols in terms of the routing protocol classifications mentioned in Chapter 2 and the three routing protocol mechanisms mentioned in this chapter.

Table 4.1: OLSR, DSR, and AODV routing protocol characteristics.

	OLSR	DSR	AODV
Routing philosophy	Proactive	Reactive	Reactive
Network structure	Hierarchical	Flat	Flat
Routing metric	Hop number (shortest path)	Hop number (shortest path)	Hop number (shortest path)
Broadcasting method	Neighbour knowledge	Simple flood	Simple flood
Maintenance	Periodically	As needed	As needed
Periodic Hello message	Yes	No	Yes on need
Use sequence numbers	Yes	No	Yes
Multiple paths	No	Yes	No
Loop free	Yes	Yes	Yes

4.4 Summary

Mobile nodes should not be restricted to operating solely in a particular Ad hoc network context. The routing scheme should also be able to cope with the performance fluctuation problem. Rather than create yet another routing protocol to address these issues, this chapter proposes a radical approach to MANET routing protocols: an Intelligent-Mobile Ad hoc Network (I-MAN) routing protocols optimisation system. The need for the proposed system arose because degradation of the routing protocol performance is always associated with the changes in the network context. The I-MAN routing protocols optimization system abstracting this problem to another level: the environment context is taken into account by a system that deduces the most appropriate/suitable protocol for the observed conditions. Then, this system, represented by the Intelligent node, informs the nodes of the routing protocol to run and thus performs optimally even in the case of continuous changes. In this chapter, a novel I-MAN system design has been introduced with this simple idea of including various routing protocols in one system and then selecting the best protocol to operate. I-MAN routing protocols optimisation system design relies on four basic components: Simulator, Modeller, Optimiser, and Switcher.

The proposed intelligent system acts like an overlay protocol that triggers routing protocols according to the needs of the network. This system is an attempt to enable a mobile node to achieve its best performance as it roams through the network, and to provide an automatic routing protocol selection and adaptation mechanism based on the current topology of the network.

4.5 References

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Chapter 5

MANET Simulation

5.1 Introduction

Utilising simulation software packages is beneficial to the testing of any new design. Simulation can save time, energy, and money as there is no need to order equipment and connect it together to set a scenario. For example, the Opnet™14 software package makes it possible to simulate any communication network for wired or wireless networks in a short time, and the scenario can also provide different services. There is no doubt about how important it is to establish a test bed for a system to measure its reliability in real the world, but this step (the test bed) should come after a successful software implementation.

This chapter presents simulations for MANET of different network sizes and average mobility utilising the Opnet™14 software package. The main contribution in this chapter is the development of a strategy to represent the collected MANET performance metrics against the network context. In Section 5.2, the MANET simulation network will be introduced; this section defines the settings for the communication model, the movement model, the simulation parameters, and the performance evaluation metrics. The network simulation results are then presented in 2D and 3D in Section 5.3. Next, Section 5.3.3 analyses the network results and Section 5.4 summarises the findings of this chapter.

5.2 MANET Simulations

MANET simulations are the first requirement or the first component needed to accomplish the I-MAN optimisation system design. The network simulations were implemented utilising the Opnet™14 modeller. This modeller includes a collection of routing protocols; each routing protocol depends on a different route discovery mechanism to establish a route to the source destination (as mentioned in Chapter 4). In this research, a proactive routing protocol (OLSR) and reactive routing protocols (DSR and AODV) were selected. For each of the three MANET routing protocols, the same MANET simulation environment was used.

5.2.1 Communication Model

Raw data packets were generated using Poisson's Inter-Arrival time at a data rate of 1 Mbps. The Poisson's regime is a model in which data is communicated by random discrete occurrences in time that obey Poisson's statistics of arbitrarily time-varying mean [1]. In this way, each node in the network generates and sends packets.

Determining how many levels of network size (the smallest and the largest network sizes to be considered) will definitely influence the number of simulations such that if the number of network size levels increases, then the number of the network simulations will increase as well (this will be explained in detail in Section 5.2.3).

For each evaluated routing protocol, several simulations were performed. The network size will increase in each simulation, starting from a network with 4 nodes (assuming that the smallest realistic network could have 4 nodes) and extending to network with 64 nodes (assuming that a reasonably large MANET could have 64 nodes). Another point worth noting is that through each simulation, the network size did not change; for example, the simulation starting and ending with a network of 64 nodes.

Consequently, the coverage area will be increased; for the first scenario, the coverage area is 500 m × 500 m. The network size will then be incremented in steps of 500 m to the maximum of 3.5 km × 3.5 km for the last scenario. These simulations were executed to mimic one hour communication time.

5.2.2 Movement Model

Each node in the simulated scenarios considered had its own Random Walk Mobility Model [2], meaning nodes moved for random directions through the whole simulation within the predefined area without any pause time.

Determining how many mobility levels and what are the slowest and the fastest network that should be considered in this research will definitely influence the number of simulations; for example, if the number of mobility levels increases, then the number of network simulations will also increase (this will be explained in detail in Section 5.2.3).

The packets from a source node to a random destination node were sent considering different levels of mobility from stationary network to reasonably fast network. Four levels of user average mobility were considered: (0 m/s), (1 m/s), (10 m/s), and (20 m/s). The latter three levels are defined by varying the speed of the mobile users. As each individual network node moved with its own trajectory and speed, the network nodes' speed were summed and averaged to determine the network mobility. Therefore, the mobility levels mentioned previously are the average mobility for the whole network.

5.2.3 Simulation Parameters

The infrastructure-less nature of a MANET, which allows network nodes the freedom to join or leave the network at any time, will continuously effect the overall network performance. Therefore, this characteristic could be represented by various parameters [3] such as number of traffic sources, node bandwidth, node power, node pause time, and all of the parameters mentioned in Chapter 3. In this thesis, two important context parameters have been considered to evaluate the network performance: the network size and the nodes' mobility.

Moreover, the number of simulation scenarios needed for modelling the network depends on two important elements:

1. The number of selected network context parameters.
2. The number of modelled routing protocols.

The simulation scenarios will increase and decrease depending on these elements, as expressed by Equation (5.1). Assuming that P_c represents the selected network context parameter, T_c is the total network context parameters as $T_c \geq 2$ and $c \geq 1$, and R_T is the total number of MANET routing protocols to be modelled.

Therefore, the total number of the created scenarios S_T can be given as:

$$S_T = \prod_{c=1}^{c=T_c} P_c \times R_T \tag{5.1}$$

In the I-MAN optimisation system design, the simulations considered two context parameters (P_C):

1. Network size level.
2. Mobility level.

Assuming that P_1 represents the first parameter that is the network size, N_{size} represents the selected network size, T_{size} represents the total number of the network selected cases, and *size* represents the selected case, where $size \geq 1$, the equation is the following:

$$P_1 = \sum_{size=1}^{size=Tsize} N_{size} \tag{5.2}$$

Assuming that P_2 represents the second parameter, namely mobility levels, M_{level} represents the selected node average mobility level in the network, T_{level} represents the total mobility level cases, and *level* represents the mobility level case, where *level* ≥ 1, then the equation is the following:

$$P_2 = \sum_{level=1}^{level=T_{level}} M_{level} \tag{5.3}$$

Assuming that $R_{protocol}$, $T_{protocol}$, and *protocol* represent the MANET routing protocol, the total number of MANET routing protocol cases used and the protocol number respectively, where *protocol* ≥ 1 and $T_{protocol}$ ≥ 2, then the equation is as follows:

$$R_T = \sum_{protocol=1}^{protocol=Tprotocol} R_{protocol} \tag{5.4}$$

Combining Equations (5.1), (5.2), and (5.3), the equation for the I-MAN simulations scenarios is as follows:

$$S_T = P_1 \times P_2 \times R_T \tag{5.5}$$

In Equation (5.5), the first parameter, P_1 mentioned in Equation (5.2), considers seven cases of network size. Representing various network sizes from small to large, the P_1 cases are 4, 9, 16, 25, 36, 49, and 64 nodes, respectively. The second parameter, P_2 mentioned in Equation (5.3), has four levels of mobility. The P_2 levels are stationary (0 m/s), low (1 m/s), medium (10 m/s), and high (20 m/s). The last parameter, R_T mentioned in Equation (5.4), considers three routing protocol. From the above it can be determined that the total number of simulations needed will be 84 (S_T = 7 × 4 × 3).

5.2.4 Performance Evaluation Metrics

Through the network simulation, many parameters that present the network performance were collected and gathered. The correlated parameters were filtered and five important parameters on which to base network performance selected; these five metrics also reflect the reaction of the other “not selected” metrics. The performance metrics adopted during the comparative analysis are as follows:

1. *Data Drop* (bits/s): the total data traffic dropped by the network nodes.
2. *Delay* (s): the end-to-end packets delay experienced by all nodes.
3. *Load* (bits/s): the total data traffic received by a all node.

4. *Retransmission Attempt* (*R. A.*) (packets): the total number of retransmission attempts by all the network nodes.

5. *Throughput* (bits/s): the total number of bits forwarded in all nodes.

5.3 Simulation Results

For each simulation scenario that ran for one hour of simulation time, the results for each respective metric were recorded and stored. In another words, the simulation network scenario collected the network's five performance metrics and presented values every 48 seconds, throughout the simulation time from the 0s to 3600s. Therefore, the metrics data collected for the five parameters in the 84 scenarios were stored in 420 data files.

The data collected from all the MANET simulation scenarios should be modelled. Before modelling data, the data should go through two stages: first, the averaging stage (explained in Section 5.3.1), then the arranging stage (explained in Section 5.3.2).

5.3.1 Averaging Data

The representative value for each performance parameter should be concluded from the simulation results. In each scenario, through all the simulation time, the average value for each performance parameter was calculated. In another words, the mean was computed for the data drop, the delay, the load, the retransmission attempts (RAs), and the throughput to represent the network performance parameters for that scenario. Therefore, for each simulation scenario, five performance values were determined. They were demonstrating the efficiency of the network performance during the one hour of simulation. Figures 5.1 through 5.5 present the averaged five performance metrics: data drop (bits/s), delay (s), load (bits/s), RAs (packets) and throughput (bits/s). These 2D performance measurers are plotted against network size, where subfigure (a) represents station network 0 (m/s), (b) relates to the average network mobility 1 (m/s), (c) relates to the average network mobility 10 (m/s), and (d) relates to the average network mobility 20 (m/s). Each subfigure contains three curves that represents the MANET operated with one of the three routing protocols OLSR, DSR, or AODV. The parameter network size was labelled as "no. of nodes" in these graphs.

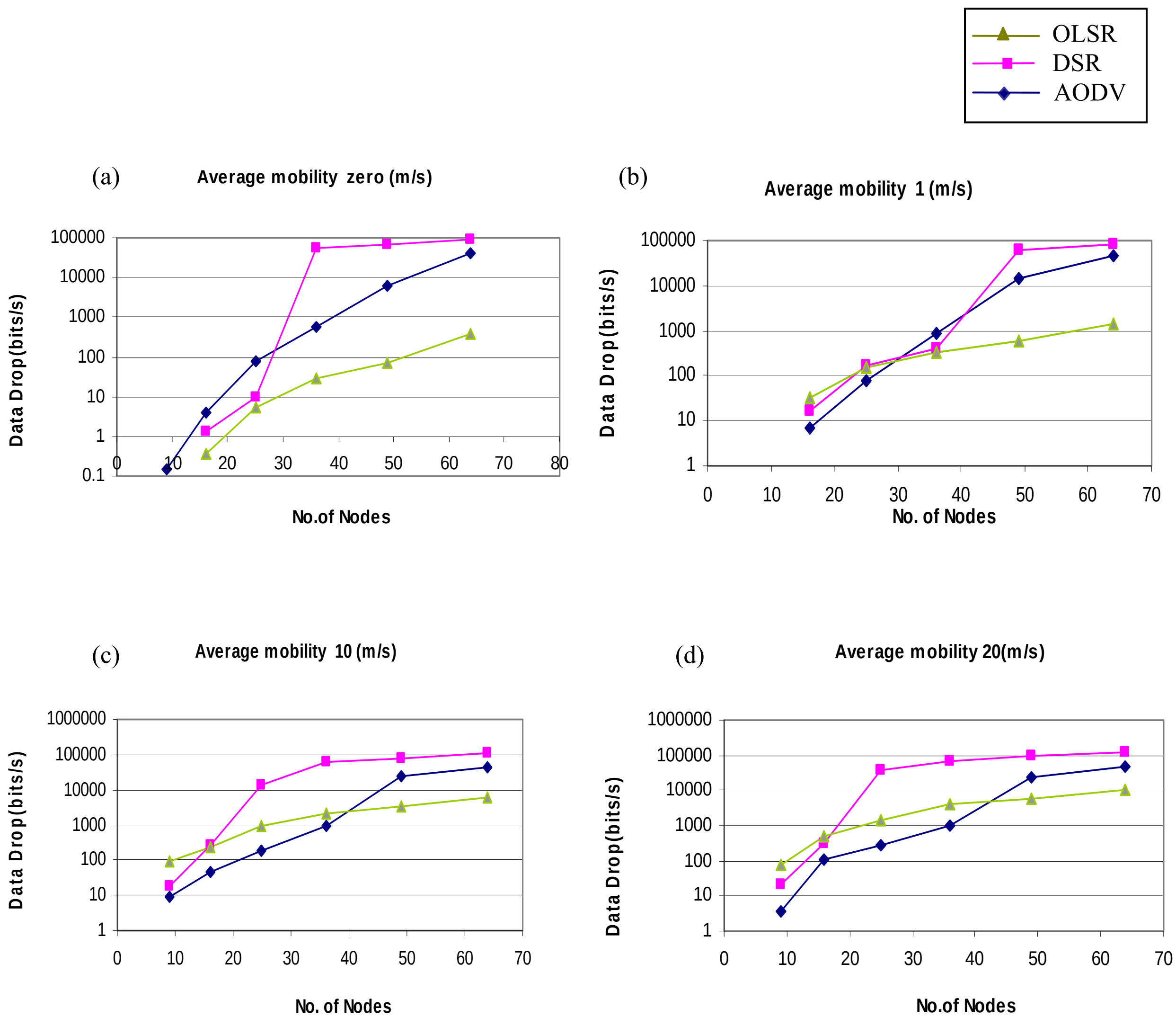

Figure 5.1: OLSR, DSR, and AODV routing protocols data drop results utilising MANET simulations with an average mobility a) 0 (m/s), b) 1 (m/s), c) 10 (m/s), and d) 20 (m/s).

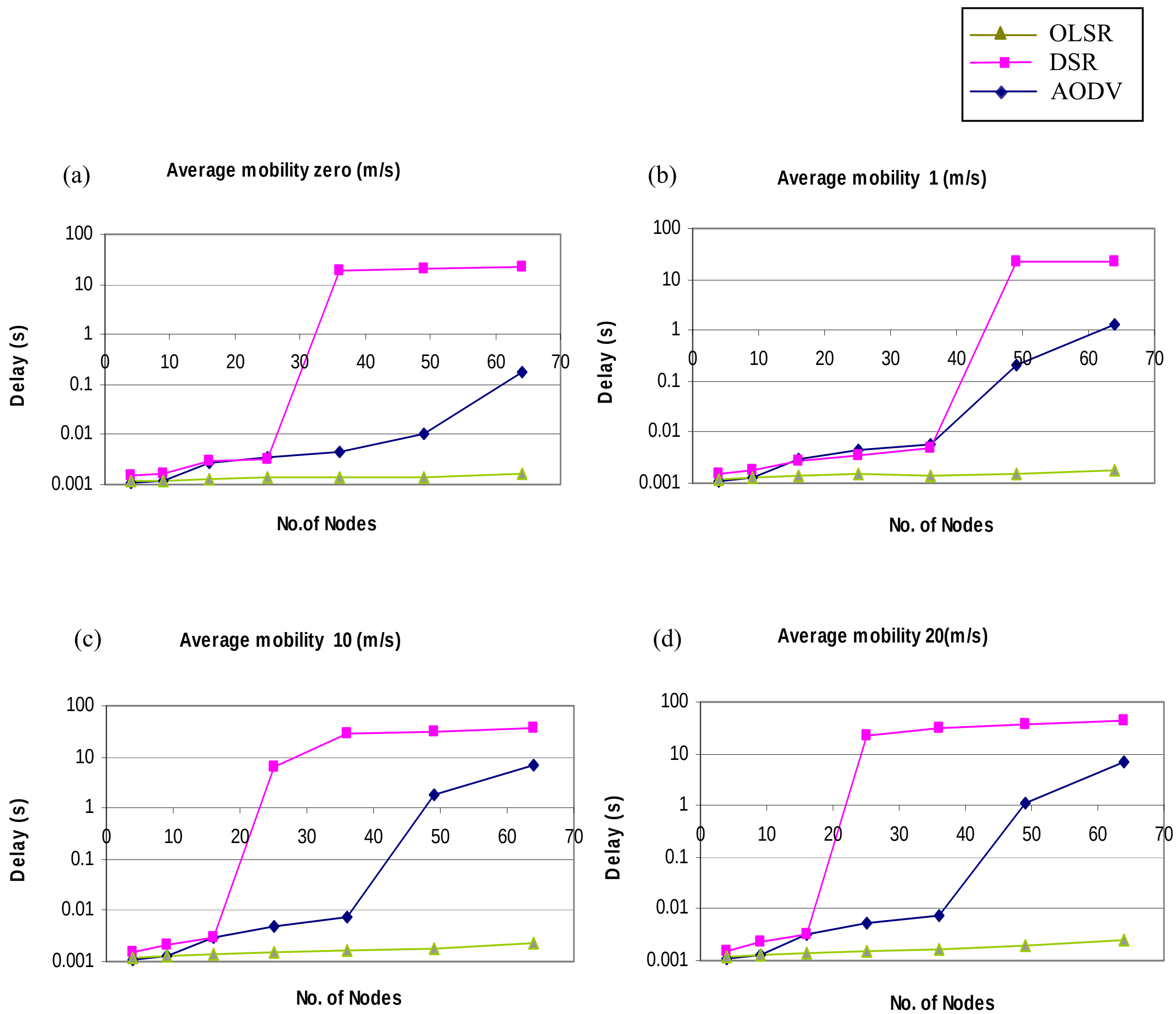

Figure 5.2: OLSR, DSR, and AODV routing protocols delay results utilising MANET simulations with an average mobility a) 0 (m/s), b) 1 (m/s), c) 10 (m/s), and d) 20 (m/s).

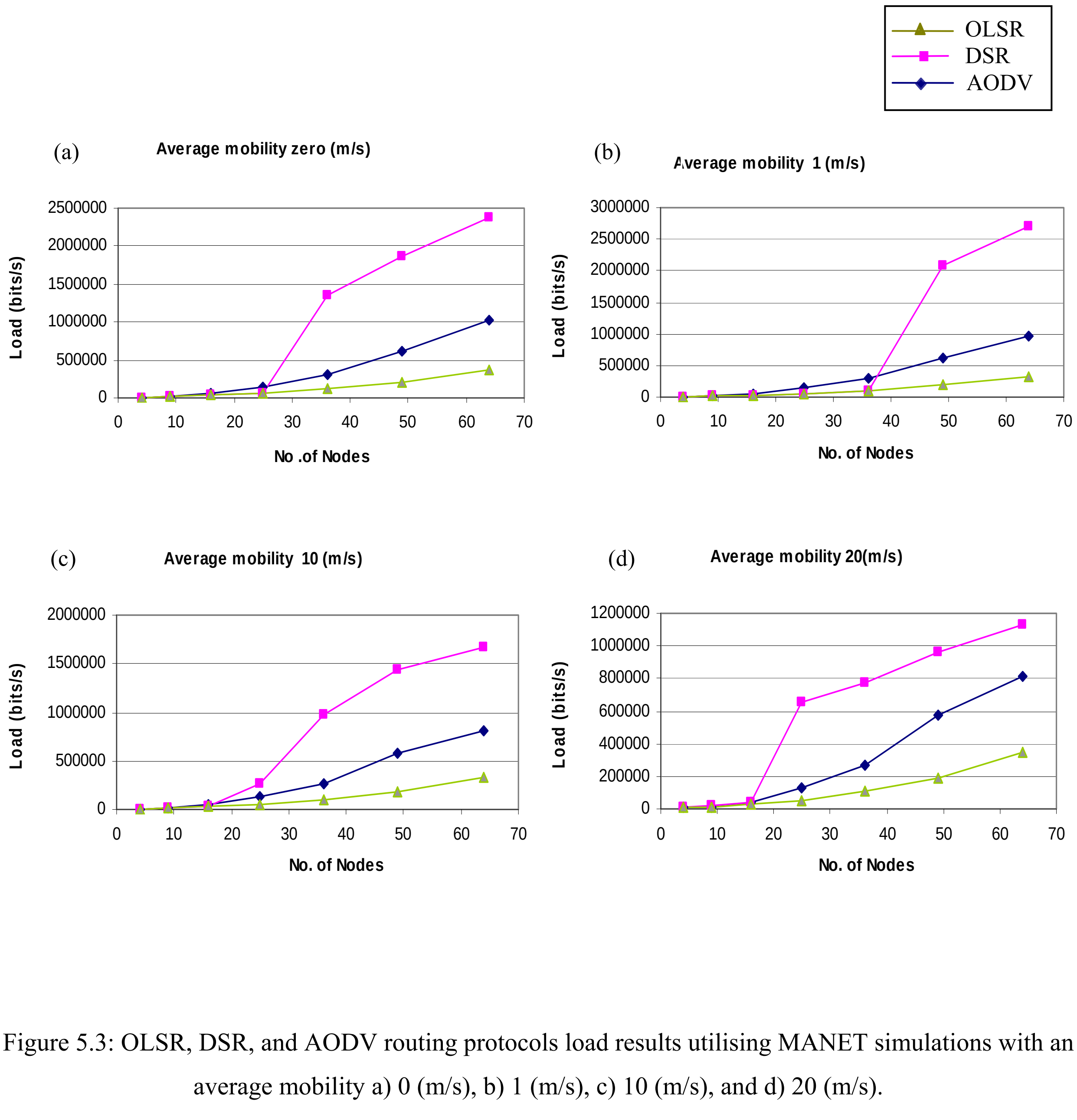

Figure 5.3: OLSR, DSR, and AODV routing protocols load results utilising MANET simulations with an average mobility a) 0 (m/s), b) 1 (m/s), c) 10 (m/s), and d) 20 (m/s).

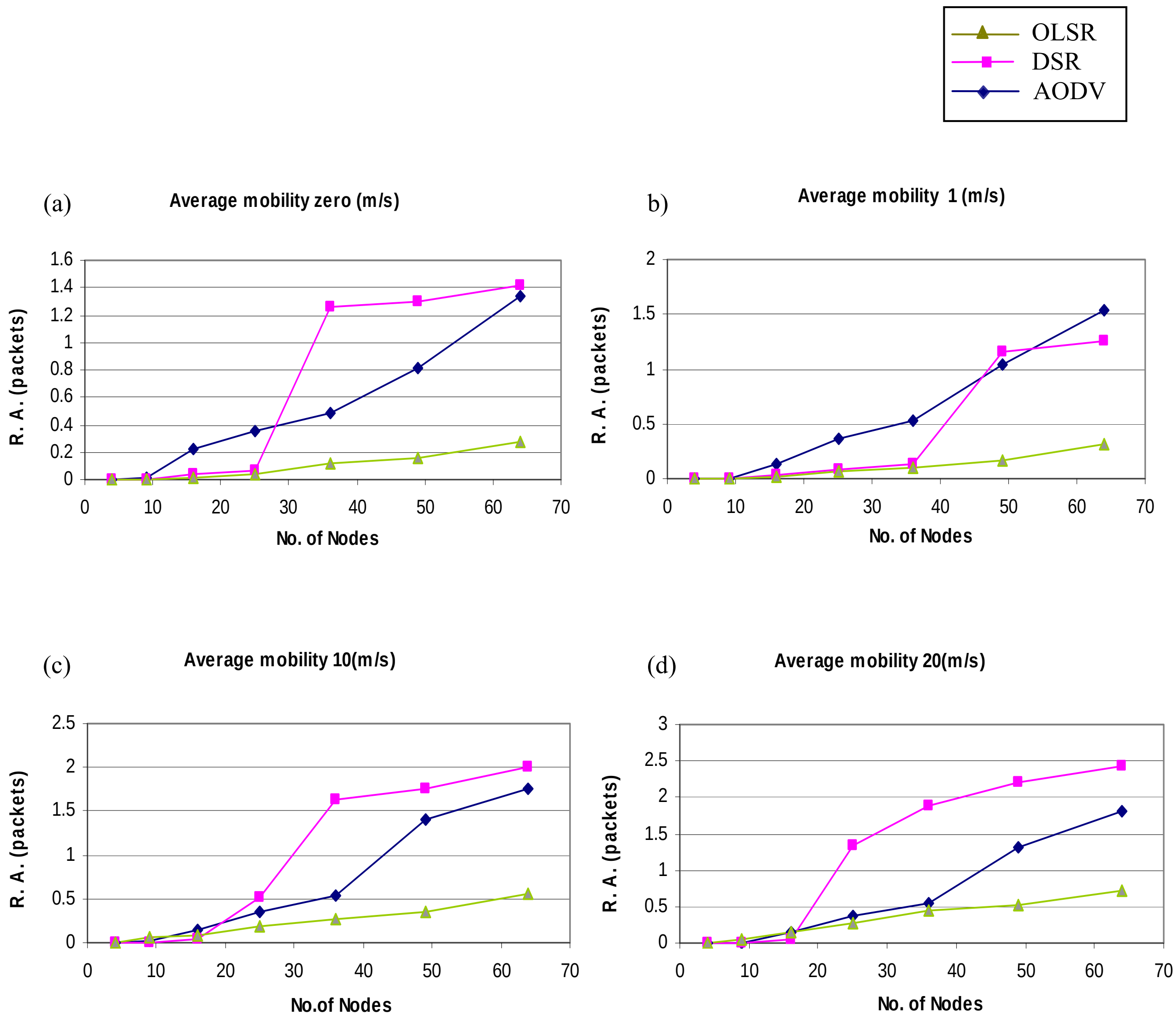

Figure 5.4: OLSR, DSR, and AODV routing protocols' Retransmission Attempt (RA) results utilising MANET simulations with an average mobility a) 0 (m/s), b) 1 (m/s), c) 10 (m/s), and d) 20 (m/s).

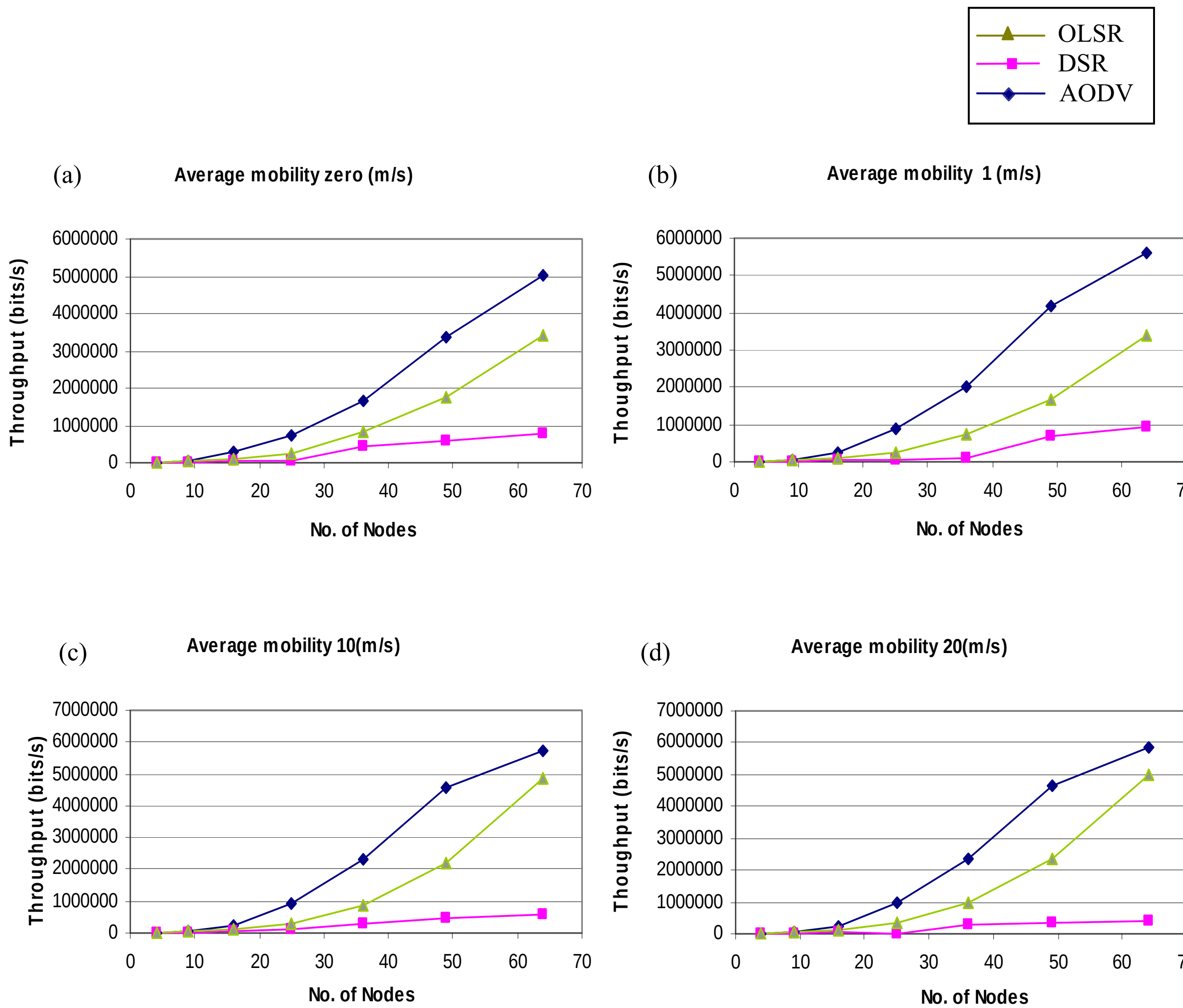

Figure 5.5: OLSR, DSR, and AODV routing protocols throughput results utilising MANET simulations with an average mobility a) 0 (m/s), b) 1 (m/s), c) 10 (m/s), and d) 20 (m/s).

5.3.2 Arranging Data Related to the Network Context

The next step is arranging the averaged data against the context in a 3D orientation, where each averaged performance metric is related to the two network contexts of network size and average mobility. In the proceeding figures, the parameter average mobility was labelled as “mobility.” The inputs were the two context parameters, no. of nodes (x-axis) and mobility (y-axis), whereas the z- axis represents the output performance parameter.

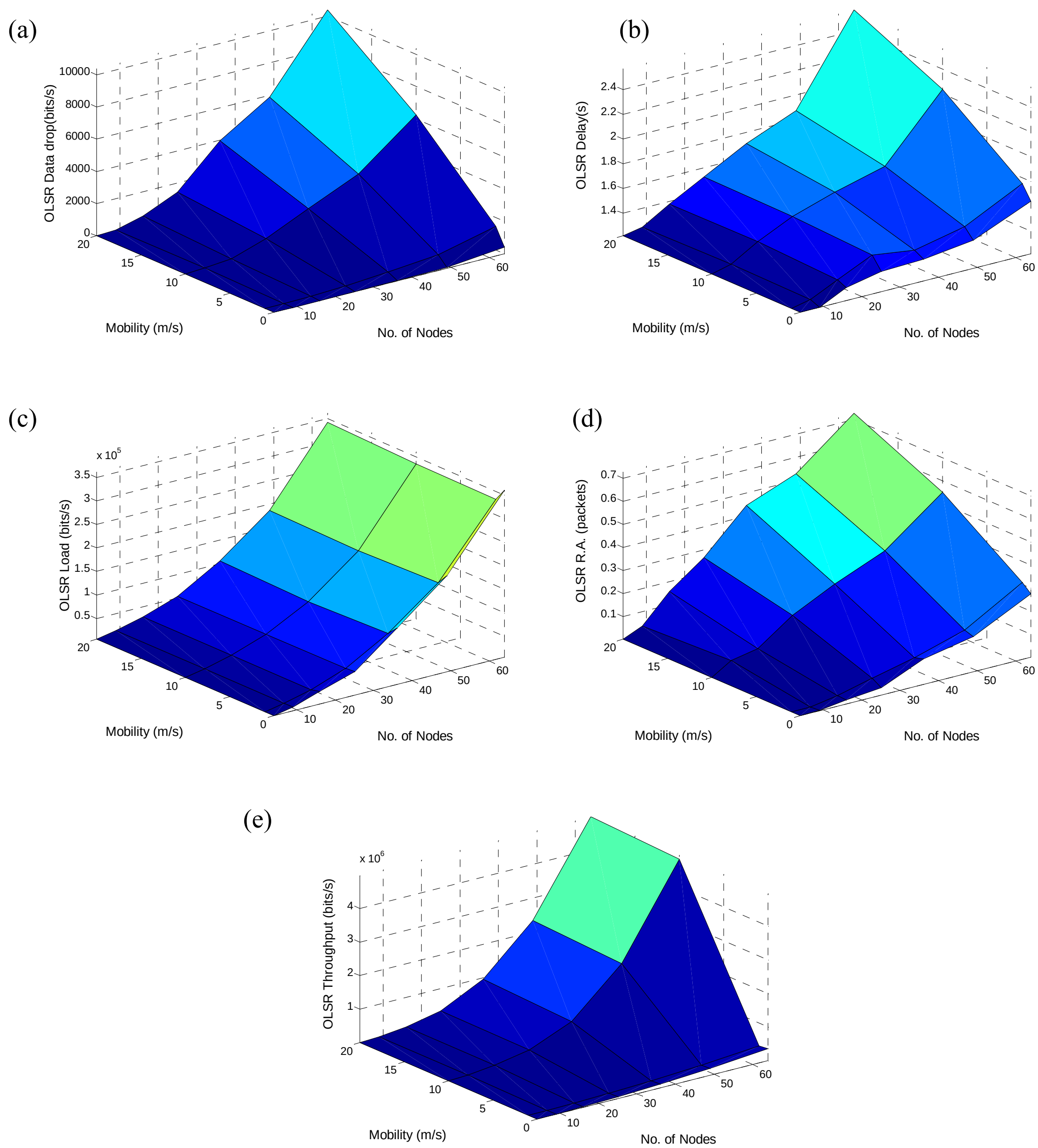

Figure 5.6: The performance metrics models for OLSR; a) Data drop, b) Delay, c) Load, d) RA, and e) Throughput.

Figures 5.6, 5.7, and 5.8 show the respective performance of OLSR, DSR, and OLSR routing protocols against the no. of nodes and mobility; the subfigures represent (a) data drop, (b) delay, (c) load, (d) RA. and (e) throughput.

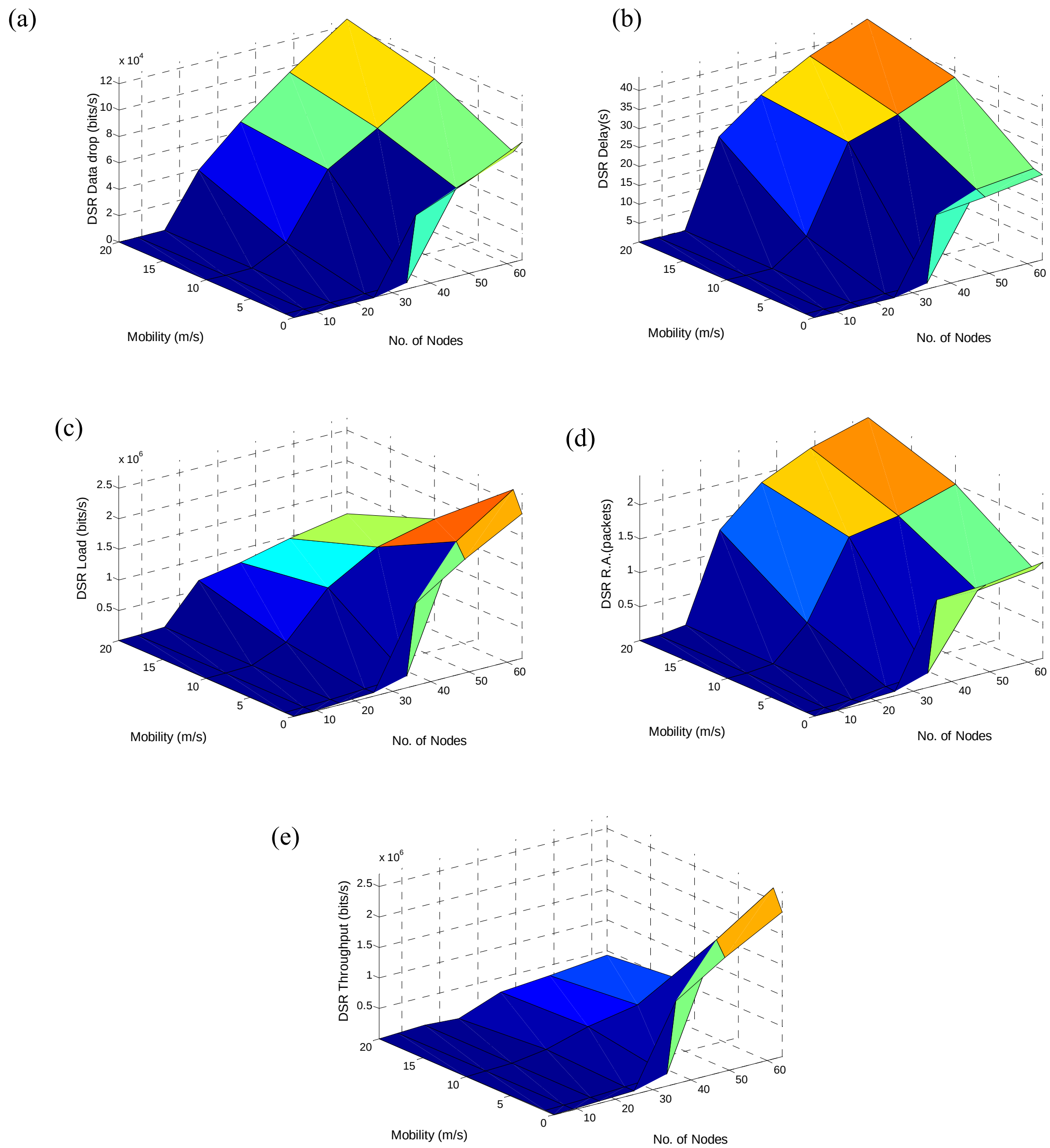

Figure 5.7: The performance metrics models for DSR; a) Data drop, b) Delay, c) Load, d) RA, and e) Throughput.

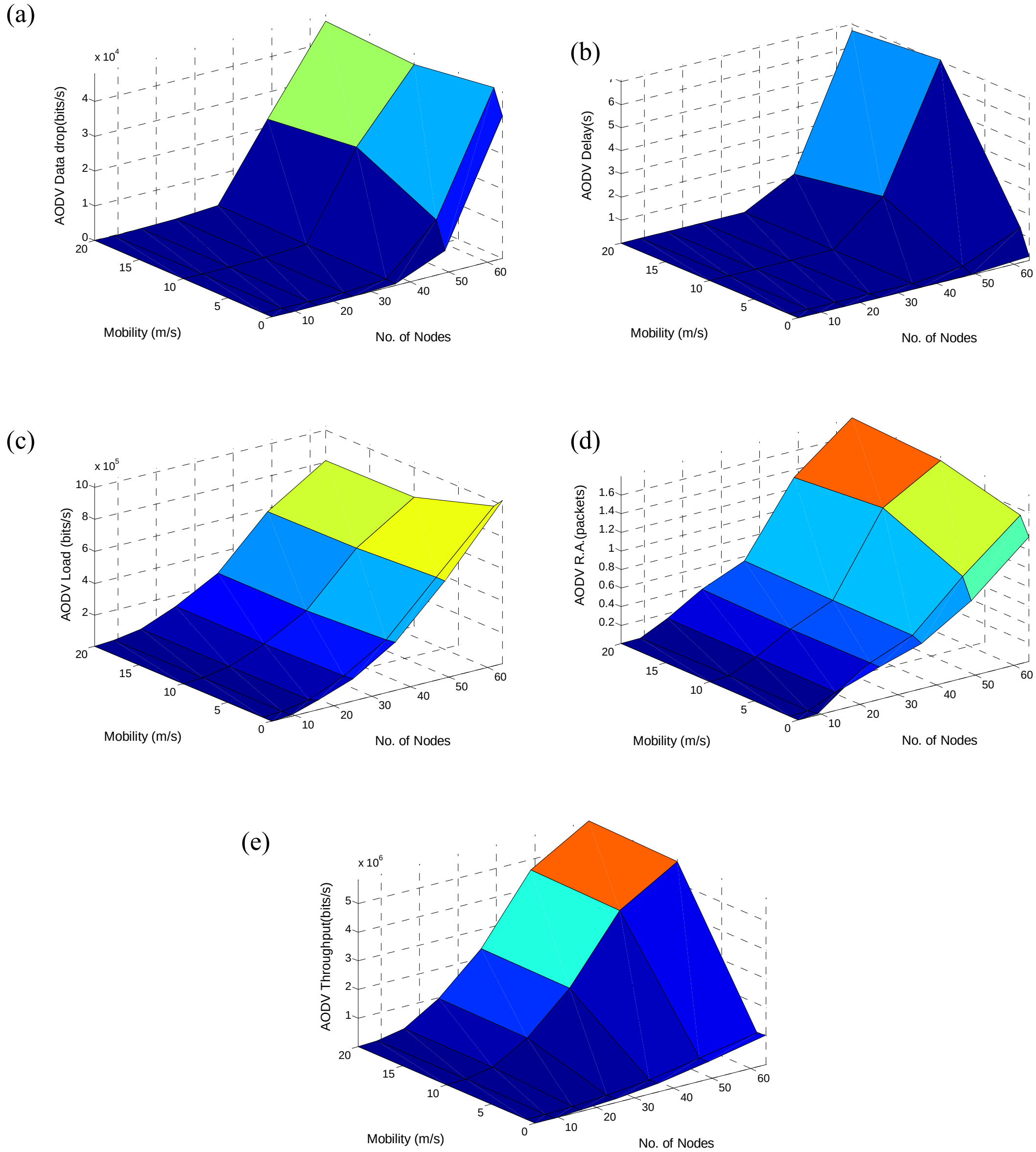

Figure 5.8: The performance metrics models for AODV; a) Data drop, b) Delay, c) Load, d) RA, and e) Throughput.

5.3.3 Results Analysis

In this section the simulation results presented in Figures 5.1 through 5.5 are analysed and discussed below.

5.3.3.1 Data Drop

In the four subfigures of Figure 5.1, it appears that there is no data drop for the 4-node network size.

Figure 5.1 (a) shows that, in spite of increasing the network size, the least data drop was shown in the network operating with an OLSR routing protocol. As OLSR is designed to handle scalable networks by implementing the MPR technique [24], OLSR proactive mechanism also secures in each MPR node a routing table that contains the routes for all possible destinations. This feature enables OLSR to deliver a good amount of data without dropping. As shown in the subfigure (a), the station network with 64 nodes has five-figure number data drop when operated with a DSR routing protocol, whereas utilising OLSR routing with the same network produced a data drop of only three-figure number.

Figure 5.1 (a) also shows that the DSR routing protocol shows less data drop compared to AODV routing protocols, for a network size of up to 36 nodes. When a network size is increased to more than 36 nodes, the routing protocols (AODV and DSR) switch positions and the network implementing AODV routing protocol achieves less data drop compared to the network that operated with DSR routing protocol. The reason behind this is that the DSR routing protocol is not designed for a scalable network because of its route cache mechanism [6]. The side effect of the incremental increase in network size is that the DSR route cache will also grow. Therefore, the DSR network will suffer from delay increment, as shown in Figure 5.2 (a), and load increment, Figure 5.3 (a), which will affect the transmission and cause a significant amount of data drop.

Figure 5.1 (b) shows the different performances for the networks operating with the three protocols. The network in this figure is dynamic with average mobility (1 m/s). For a network size of up to 36 nodes, the least data drop is shown with AODV, then DSR, followed by the worst network operating on OLSR. With a network size of 36 nodes, the best routing protocol is OLSR, followed by DSR, and then AODV; whereas with a network size of 49 nodes, the best routing protocol is OLSR, followed by AODV, and then DSR.

In Figure 5.1, (c) and (d) clearly show that for a network size of less than 25 nodes, the least data drop is for a network which operates on AODV, followed by a network which operates on DSR, and; the worst results are for a network operating OLSR. With a network size ranging from 25 to up to 49 nodes, the best routing protocol is AODV, followed by OLSR, and then DSR. With a network size ranging from 49 to up to 64 nodes, the best routing protocol is OLSR, followed by AODV, and DSR. Furthermore, the results in Figure 5.1 (c) and (d) show that the AODV routing protocol is efficient for a dynamic network with high and medium mobility [8].

In Figure 5.1, (a) and (b) when the mobility is low, 0 (m/s) or 1 (m/s), the data started to drop for any network size greater than 16 (except in the AODV graph which started from 9, as shown in Figure 5.1 (a)); whereas when the mobility is medium, 10 (m/s), or high, 20 (m/s), in Figure 5.1 (c) and (d), the data started to drop for smaller network sizes, as compared to Figures 5.1 (a) and (b) in which the data started to drop from any network size greater than 9 nodes. Approximately, the AODV routing protocol was the only protocol in which the network data drop increased linearly in the log scale by increasing the average mobility and the network size.

5.3.3.2 Delay

As shown in Figure 5.2 (a), the delay for the networks using AODV and DSR protocols are approximately the same for a network size of up to 36 nodes. Once this size is exceeded, a rapid increment happens to the network delay that operates DSR against an acceptable delay for the network that operates AODV, which will continue through the rest of the simulation. However, the OLSR's delay is a significant small amount that does not affected by the network size increase through the simulation compared with the other two protocols; that is due to OLSR proactive mechanism that stores update table for the whole network and adopts MPR technique that selects the effective neighbour nodes to retransmit the source packets. As shown in subfigure (a), a station network of 64 nodes has a delay equivalent to a fraction of a second using OLSR routing protocol, whereas the same network delay operating DSR reaches a one figure number.

In Figure 5.2 (b), the network is operated with average mobility 1 (m/s); the three routing protocols show the same attitude as previously seen in Figure 5.2 (a) with a rapid shift in the delay of a network operating DSR, for a network size of up to 49 nodes.

In Figure 5.2, subfigures (c) and (d) show how medium and high mobility can affect the network delay. The network operating with DSR showed rapid delay increment for a network size greater than 25 nodes, whereas the network operate with AODV showed rapid delay increment for network size greater than 49 nodes.

5.3.3.3 Load

Figure 5.3 (a) shows that the stationary networks operating with the three protocols have approximately the same load until the network size is increased to more than 25 nodes, at which point networks operating with DSR have the worst load for the duration of the simulation.

In Figure 5.3 (b), when the network's average mobility is 1 (m/s), the networks operating with OLSR and DSR have less load than the networks operating with AODV. The load for DSR's network is clearly better than the load for the AODV's network, up to a network size of more than 36 nodes; beyond this point, the load for DSR's network suffers rapid increment. This observation is supported by the fact that "the scalability affects DSR routing protocol" [14].

In Figure 5.3, subfigures (a), (b), (c), and (d) show that the load for the OLSR's network was significantly less due to the MPR technique, in spite of the increment in network scalability and mobility, especially in subfigures (c) and (d). For networks that operate with On Demand protocols, AODV and DSR have higher load due to the routing establishment mechanism.

5.3.3.4 Retransmission Attempt (RA)

Figure 5.4 shows that the network operating with an OLSR protocol has delivered most of the network packets. Therefore, the need for RA is less than the other networks operated with AODV and DSR routing protocols. In a network that operates with a OLSR routing protocol, the node keeps all the neighbouring nodes' addresses in the routing table; this characteristic makes it easier for the node to deliver the packets to their destination. However, networks that operate on the On Demand routing protocols, AODV and DSR, have to find the destination through establishing a new route if the node does not have the address in its routing table. For this reason, many packets may not be delivered and will demand another retransmission attempt.

Figure 5.4 (a) shows that a network operating the DSR routing protocol has less RA than a network that operates on AODV for a network size of up to 25 nodes, whereas for a network size more than 25 nodes AODV's network shows less RA compared to DSR's network.

In Figure 5.4 (b), the AODV's and DSR's network behaviour were similar to their behaviour in Figure 5.4 (a) as DSR's network has less RA than a network that operates on AODV routing protocol, for a network size increased to up to 36 nodes. When the network size is 49 nodes, the network operates on AODV has fewer RA than the DSR network. However, when the network size is 64 nodes, the network operating on DSR has fewer RA than the AODV network.

Increasing the average mobility, as shown in Figures 5.4 (c) and (d), increases the packets' retransmission attempts for a DSR network with a size of 16 nodes. In spite of the increments in the average mobility, AODV sustains the previous rate of RA which proves the fact that AODV is designed for a dynamic network [8].

5.3.3.5 *Throughput*

The four subfigures of Figure 5.5 show that the best throughput was for a network operating with AODV, followed by a network operating with OLSR, and lastly a network operating with a DSR routing protocol. The AODV routing protocol was able to forward more packets with the mechanism that quickly establishes routes and then forwards more packets.

5.4 Summary

Relating the collected MANET performance parameters against the two network context parameters considered in this thesis and presenting them visually in 3D graphs, this chapter describes a novel, approach to MANET that has not be explored in previous research. Combining the network contexts in *one* graph to present their effects on a particular network performance will dispel the confusion and set a standard of comparison between the protocols.

This chapter also describes the simulation results for the three MANET protocols AODV, DSR, and OLSR operating in different scenarios, with multiple network sizes and multiple average mobility (these results also show the protocols characteristics that having been discussed in Chapter 4). A short summary and findings for each performance are given below.

The graphs in Figure 5.1 draw a general conclusion that as the mobility increases; the data drop will increase as well. Also, the figure shows that increasing the mobility affects the data drop for the DSR operated network more than the ones operated with OLSR and AODV routing protocols, as the DSR data drop for a network of 64 nodes reached ten four-figure number (bits/s) with average mobility of 20 (m/s).

Figure 5.2 clearly shows that, through the whole simulation for the four subfigures, the best delay is for a network operating on an OLSR routing protocol, which is related to the MPR mechanism (less message), The network operating on AODV is second; this may be accounted for by the AODV sequence number mechanism (drop duplicated messages). The network with the DSR routing protocol is last due to the DSR cache route mechanism (carry the full path), as the network scalability and mobility affects DSR routing protocol delay. As shown in subfigure (a), when the network size is 36 nodes, DSR's delay rapidly increases. Whereas in subfigures (c) and (d), when the average mobility increases to 10 (m/s) or 20 (m/s), respectively, the delay for DSR was increased rapidly with network of 25 nodes (smaller that in subfigure (a)).

In general, Figure 5.3 showed that the load for the networks operated with On Demand protocols were affected by scalability, especially DSR. As shown in subfigure (a), the networks' load starts to increase with a stationary network of 25 nodes and higher. As shown in (b), the loads of networks with average mobility 1 (m/s), will start to increase with a network size of 36 nodes and higher. When the networks average mobility is increased to 10 (m/s) and 20 (m/s) respectively, as shown in (c) and (d), the network will suffer from high load that starts to increase past a network size of 16 nodes. The movement of the network nodes breaks the early established route, creating a demand for a *Route discovery* to establish a new route, which in turn causes load over the network. The load for AODV's network was less than the load for DSR's network the majority of the time; this is related to hop by hop and the sequence number mechanisms AODV employs. These mechanism will reduce the load by dropping (that is not forwarding) the packets with old sequence numbers, such that only those packets that have the updated sequence number will be forwarded.

Also, Figure 5.3 showed that, for the four subfigures through the simulation time, the least load was for the network that operated on the OLSR routing protocol.

From Figure 5.4, it is clearly shown from the four subfigures that the fewest packets' retransmission attempts were accrued for the network that operated on OLSR routing protocol, with the AODV operated network second and the DSR network third.

Figure 5.5 shows that the best throughput was for a network that operated on AODV, followed by a network that operated on OLSR, and lastly, a network that operated on DSR.

The results show that OLSR has the best results in terms of delay, load, and retransmission attempts, whereas AODV has the best throughput. AODV and OLSR perform well with large network sizes and high mobility, whereas DSR protocol performs at an acceptable level with lower mobility and smaller network sizes.

The simulation results proved and confirmed that in certain contexts, one of the routing protocols will give a better performance than the other. However, when the context changes, the first protocol's performance will degrade whereas the second protocol's performance will improve.

5.5 References

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Chapter 6

Modelling Methodology

6.1 Introduction

The model's chief duty is to provide a simplified view of a complex reality. Therefore, the scientific model should represent the studied characteristics in a logical way that will yield a realistic view. The aim of creating this non-mathematical model is to construct a formal system for which reality is the only interpretation [1].

In this chapter, two modelling techniques are considered: the empirical modelling technique represented by the regression equation (RE), and the Artificial Intelligence (AI) modelling technique represented by Artificial Neural Networks (ANN) and Neuro-Fuzzy (NF). As such, there are two main contributions in this chapter; the first is employing the modelling techniques to create models to represent the MANET's context and performance, and the second is comparing and selecting one of these techniques to be used as the Modeller in I-MAN optimisation system.

The chapter is organised as follows: in Section 6.2, the empirical model is defined and the regression equation explained as an example of such a model; in Section 6.3, first the Artificial Intelligence modelling methods are defined and then two artificial intelligent methods, ANN and NF, described and explained in detail; in Section 6.4, the aforementioned modelling techniques are employed with MANET; in Section 6.4.4, a comparison between the three created MANET models is presented; and finally, Section 6.5 includes the summary and relevant conclusions.

6.2 Empirical Modelling

The word *empirical* in the American Heritage Dictionary [2] denotes information gained by means of observation, experience, or experiment. Therefore, the empirical relationship will be based solely on observation rather theory, as an empirical relationship requires only confirmatory data irrespective of a theoretical basis.

As opposed to analytical modelling, empirical modelling is a popular approach to develop process models using experimental data, which is commonly welcomed by industries [3]. If a theoretical explanation is found for what were initially empirical relationships, then the latter are no longer considered empirical. These empirical relationships are merely approximations. Although in practice they may be so accurate as to make this distinction otherwise unnoticeable, at other times the relationships may later be found to only hold under certain specific conditions, reducing them to special cases. The regression equation technique is a popular empirical technique which will be discussed in the proceeding section.

6.2.1 Regression Equation Models

An empirical relationship will create a mathematical statement and one or more empirical relationships will form an empirical equation. A regression model can be expressed as a mathematical equation that characterizes a response metric as a function of the independent factors and a set of parameters. The predicted performance y for the regression model is given in the form of a polynomial equation. The latter could be either a linear equation of the first order, or a second order equation with first order interaction, as in Equation (6.1):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon \qquad (6.1)$$

The polynomial equation could also be in the form of a third order equation as shown in (6.2), which is cubic with second or higher order interaction:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{iij} x_i^2 x_j + \sum_{i=1}^{k} \beta_{iii} x_i^3 + \varepsilon \qquad (6.2)$$

where: k is the number of factors; β_0 is the mean of y; β_i, β_{ij}, β_{ii} ,β_{iij}, and β_{iij} represent the regression coefficients; and finally, x_i and x_j are the factors' value for network factor X_i where $j \leq k$. The advantage of the regression approach is that it results in a physical equation that can be manipulated to allow for the capture of both the main and interactive effects among factors.

The regression equation has been involved in predicting MANET performance, as in paper [4] wherein the regression equation develops a performance index and statistical model that can be used as an objective measure in the evaluation and comparison of Ad hoc networking protocols. Nogueira et al.[5] also employed a linear regression equation to build a MANET framework. Moreover, second order polynomial equations in paper [6] helped to model different MANET connectivity levels.

6.3 Artificial Intelligent Modelling Methods

Modelling plays a very import role in designing an artificial system because in modelling one tries to uncover what actually happens in the natural system. The artificial models are data driven models; that means they rely on pre-defined functions and AI to structure the networks models. The artificial models are not empirical models, as they are not the product of mathematical equations alone.

The model [7] characteristics include:

a. Reproduction of some features of the natural system it is supposed to describe.

b. A formulation that should be consistent with what is known about the considered natural system; parameters cannot take arbitrary values, the mechanisms and structures of the model must have some biological plausibility.

c. Testable predictions; ideally all the variables and the parameters should be accessible to experiment.

6.3.1 Artificial Neural Networks Models

Artificial Neural Networks (ANN) are physical cellular networks that are able to acquire, store, and utilise experimental knowledge [8]. This technique is a computer-based algorithm which is modelled on the structure and behaviour of the neurons in the human brain.

Artificial neural networks are composed of simple elements operating in parallel. As in nature, the network function is determined largely by the connections between elements. A neural network can be trained to perform a particular function by adjusting the values of the connections (weights) between elements [9]. ANN can be trained to recognize and categorize complex patterns [10].

6.3.1.1 ANN Training Methods

Neural networks are commonly trained such that a particular input guides to a specific target. Therefore, the network is trained based on a comparison of the network output and the target, until the network output matches the target. A large number of input/target pairs are needed to train a network. This training method, called the *supervised* method, is a popular method. Two other methods, the *unsupervised* and the *direct design,* are also useful for training networks as a network can be obtained without previous training. Unsupervised networks can be used, for instance, to identify groups of data. Also, certain types of linear networks and Hopfield networks are examples of such direct design [11]. In summary, there are a variety of design and learning techniques that enrich the choices available to the user [12].

6.3.1.2 ANN Architecture Types

There are two types [13] for neural network architecture: feed-forward networks or feedback networks.

The feed-forward networks permit signals to travel from the input to the output in only one way, which means that the output of any layer does not affect that same layer. This architecture is extensively used in pattern recognition.

The feedback networks can have signals travelling in both directions by introducing loops in the network. Feedback networks (feed-forwarded back propagation) are very powerful networks and can get extremely complicated. Feedback networks are dynamic, or in a state of continuous change, until they reach an equilibrium point. They remain at the equilibrium point until the input changes and a new equilibrium needs to be found. Feedback architectures are also referred to as interactive or recurrent, although the latter term is often used to denote feedback connections in single-layer organizations.

6.3.1.3 ANN Layers

In general, an ANN consist of three layers (or groups) of units, wherein a layer of “hidden” units connects a layer of “input” units to a layer of “output” units [13]. In the input units, the raw information is fed into the network. The hidden unit is determined by the input units and the weights on the connections between the input and the hidden units. Finally, the output layer is determined by the hidden units and the weights between the hidden and output units.

The single-layer network will have one hidden layer, whereas the multi-layer network will have multi-layer hidden layers. Multiple-layer neural networks are quite powerful; the more neurons in a hidden layer, the more powerful the network will be. For instance, a network of two layers, in which the first layer is sigmoid and the second layer is linear, can be trained comparatively well to approximate any function.

6.3.1.4 ANN Functions

As mentioned previously, the behaviour of ANNs depend on both the weights and the input-output function (transfer function) that is specified (pre-defined) for the units. Typically, the function considered is rough approximations and falls into one of three categories [13]:

1. **Linear (or ramp) unit**: the function output is proportional to the function total weighted input.

2. Threshold unit: the function output is set at one of two levels, depending on whether the total input is greater or less than the threshold value.

3. Sigmoid unit: the function output varies continuously with the change in the input. A sigmoid function, such as tanh(x), is not a linear function and shows a greater similarity to real neurons than that of the linear or threshold units.

In MANET, ANN was useful as a predictor in paper [14]. This network utilised two types of neural networks, Multi-Layer Perceptron (MLP) network and Radial Basis Function (RBF) network, to predict a delay scheme for mobile wireless networks. The neural networks based on the nodes' past experience of the network traffic conditions predicted the intelligent delay for future network traffic conditions.

6.3.2 Neuro-Fuzzy Models

Jang [15] proposed hybridizing ANN with fuzzy logic [16] to create an Adaptive Network Fuzzy Inference System (ANFIS) [17]. In another words, ANFIS is a fuzzy inference system implemented in the framework of adaptive networks. The popular term for this intelligent system is the neuro-fuzzy (NF) system. This system synergizes the two mentioned techniques by combining the human-like reasoning of fuzzy systems with the learning capacity and connectionist structure of neural networks. Inspired by Takagi-Sugeno-Kang (TSK) or the Sugeno accurate modelling approach [18], ANFIS performs the identification of an input-output mapping in the form of a set of N input-output examples, with a fuzzy architecture.

The ANFIS architecture has been employed to model non-linear functions, identify nonlinear online components in a control system, and predict a chaotic time series. The main strength of NF systems [19] is its universal approximations with the ability to solicit interpretable IF-THEN rules, as the system has the fuzzy reasoning with the network calculation. The neuro-fuzzy system solved the two conflicting requirements in fuzzy modelling: interpretability versus accuracy.

In order to model complex nonlinear systems [17], the ANFIS model carries out input space partitioning that splits the input space into many local regions from which simple local models are employed. The ANFIS uses fuzzy *mf*s for splitting each input dimension; the input space is covered by *mf*s with overlapping, which means that several local regions can be activated simultaneously by a single input. Membership functions (*mf*s) were first introduced in Zadeh's paper "fuzzy sets" [20].

6.3.2.1 NF System Layers

ANFIS can be demonstrated in a five-layer network structure, as shown in Figure 6.1. It can be described as a multi-layered feed-forward neural network.

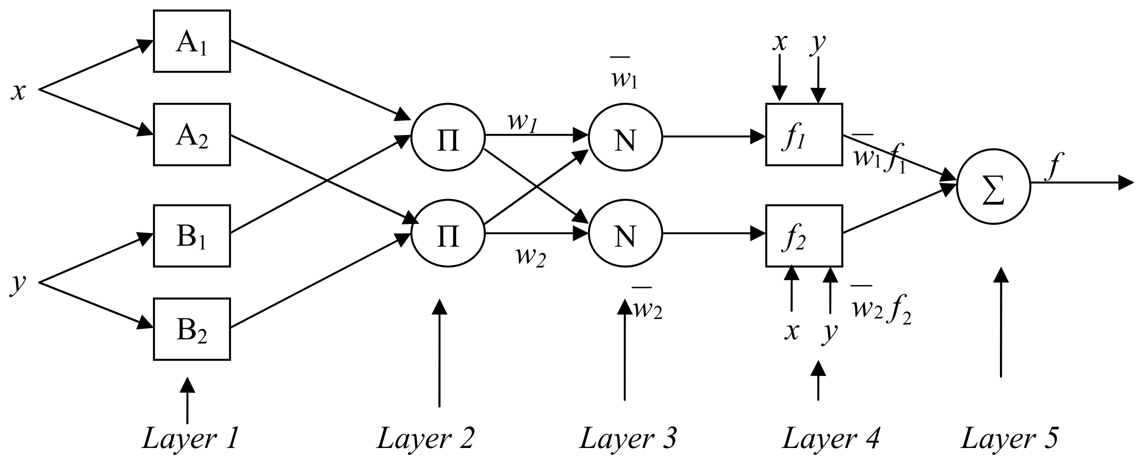

Figure 6.1: ANFIS architecture [17].

The first layer executes a fuzzification process that includes labelling each input. In the figure above, the ANFIS structure has two inputs, *x and y*, where each input considered four labels; A_1, A_2, B_1, and B_2.

The most popular function used to transform the input in *mf* is the Gaussian function, where *mf* has a bell-shaped function with maximum value equal to 1 and minimum value equal to 0. Both Equations (6.3) and (6.4) show implementation of the Gaussian function in Figure 6.1 for two inputs, *x* and *y,*

$$mf_{A_i}(x) = e^{-(x-c_i)^2 / 2d_i} \tag{6.3}$$

$$mf_{B_i}(y) = e^{-(y-c_i)^2 / 2d_i} \tag{6.4}$$

where *c* and *d* are the *mf*s' parameters that affected *mf*s shape; *c* positions the centre of the peak; and *d* controls the width of Gaussian bell.

The second layer in Figure 6.1 executes the fuzzy AND of the antecedent part of the fuzzy rules,

$$w_i = mf_{A_i}(x) \times mf_{B_i}(y), \quad \text{where } i = 1, 2 \tag{6.5}$$

The third layer in Figure 6.1 normalizes the membership functions (*mf*s),

$$\overline{w_i} = \frac{w_i}{w_1 + w_2}, \qquad \text{where } i = 1, 2 \tag{6.6}$$

The fourth layer in Figure 6.1 executes the consequent part of the fuzzy rules using the linear function,

$$f_1 = p_1 x + q_1 y \tag{6.7}$$

$$f_2 = p_2 x + q_2 y \tag{6.8}$$

and finally, the last layer in Figure 6.1 computes the output of the fuzzy system by summing up the outputs of the fourth layer.

$$f = \overline{w_1} f_1 + \overline{w_2} f_2 \tag{6.9}$$

The ANFIS approximation ability to adopt models will depend on the resolution of the input space partitioning, which is determined by the number of *mf*s in ANFIS and the number of layers.

In the MANET literature, NF has been used in optimisation, but to our knowledge, there has heretofore been no attempt to model MANET parameters with the NF system.

6.4 MANET Models

In this research, data is needed to create the models for a MANET. These data were generated using the Opnet^{TM}14 Simulator (mentioned in Chapter 4). The data information related to the 3D MANET graphs was ready to be modelled. The regression equation, ANN, and NF defined in the previous sections were considered to model MANET; therefore, the data was fed to the three modelling techniques. The network contexts considered as inputs included no. of nodes and mobility, and the network performance considered as outputs included data drop, delay, load, RA and throughput.

6.4.1 MANET Regression Models

The Essential Regression software package [21] was implemented to derive the Regression Equation (RE) models; this package analyzes quantitative data using polynomial and multiple linear regressions in a straightforward and understandable manner.

Table 6.1 shows five equations that represent the output performance parameters for each routing protocol. Based on either Equation (6.1) or Equation (6.2) in Section 6.2.1, the MANET regression equations were either second or third order, where N is the network size and M is the average mobility.

Table 6.1: MANET performance parameters' regression equations results from operating the routing protocols OLSR, DSR, and AODV.

OLSR	$DataDrop = 59.1 - 10.11N - 19.5M + 0.3N^2 + 2.9NM + 0.1M^2 + 0.096N^2M - 0.06NM^2.$ $Delay = 0.001 + 0.00003N + 0.00004M - 8.03*10^{-7}N^2 + 2.3*10^{-7}NM - 5.86*10^{-6}M^2 + 8.06*10^{-9}N^3$ $+1.3*10^{-8}N^2M - 1.8*10^{-8}NM^2 + 1.9*10^{-7}M^3.$ $Load = 6848.9 - 62.1N + 704.2M + 84.2N^2 - 90.4NM - 22.6M^2 + 0.35N^2M + 2.87NM^2.$ $R.A. = 0.00094 - 0.0003N - 0.003M + 0.000071N^2 + 0.00082NM + 0.00003M^2 - 5.02*10^{-6}N^2M - 0.000005NM^2.$ $Throughput = 158510.1 - 13396.3N - 76914.85M + 211.7N^2 + 4168.8NM + 4685.71M^2 + 98.5N^2M - 344.8NM^2.$
DSR	$DataDrop = 2482245 - 36443N - 159494M + 149.15N^2 + 170.9NM + 19962M^2 - 1.186N^3 - 0.67N^2M - 4.3NM^2 - 61.9M^3.$ $Delay = 7.5 - 1.3N - 4.6M + 0.057N^2 + 0.08NM + 0.58M^2 - 0.00052N^3 - 0.00058N^2M - 0.001NM^2 - 0.02M^3.$ $Load = 3038263.2 - 654413N - 991358M + 316345N^2 + 1557.9NM + 135273M^2 - 24.4N^3 - 46.6N^2M + 13.97NM^2 - 453.3M^3.$ $R.A. = 0.38 - 0.06N - 0.31M + 0.003N^2 - 0.004NM + 0.04M^2 - 0.00003N^3 - 0.00004N^2M - 0.00002NM^2 - 0.001M^3.$ $Throughput = -1526368 + 54049963N + 458165M + 639.9N^2 - 3007.04NM - 21699M^2 - 34.93N^2M + 165.4NM^2.$
AODV	$DataDrop = 24153 + 373.15N + 330101M - 26.6N^2 - 20.9NM - 455.7M^2 + 0.5N^3 - 0.109N^2M + 1.6NM^2 + 14.4M^3.$ $Delay = -0.448 + 0.109N - 0.107M - 0.005N^2 + 0.002NM + 0.008M^2 + 0.00005N^3 + 0.0002N^2M - 0.0005NM^2 - 6.86*10^{-6}M^3.$ $Load = 446881 - 865635N - 63543M + 580.8N^2 - 78.4NM + 10386M^2 - 3.3N^3 - 4.76N^2M + 13.01NM^2 - 40.04M^3.$ $R.A. = -0.08 - 0.002N + 0.06M + 0.0007N^2 - 0.006M^2 - 4.1*10^{-6}N^3 + 0.0002M^3.$ $Throughput = 6834971 - 924809N - 4215009M + 33954N^2 + 114308NM + 489817M^2 - 30.5N^3 + 33.7N^2M - 4447NM^2 - 14725M^3$

The regression equations for OLSR's data drop, load, RA, and throughput are square equations with second order interaction, whereas OLSR's delay regression equation is a cubic equation with second order interaction. The equations modelled the performance parameters for OLSR, as shown in subfigures (a), (b), (c), (d), and (e) in Figure 6.2.

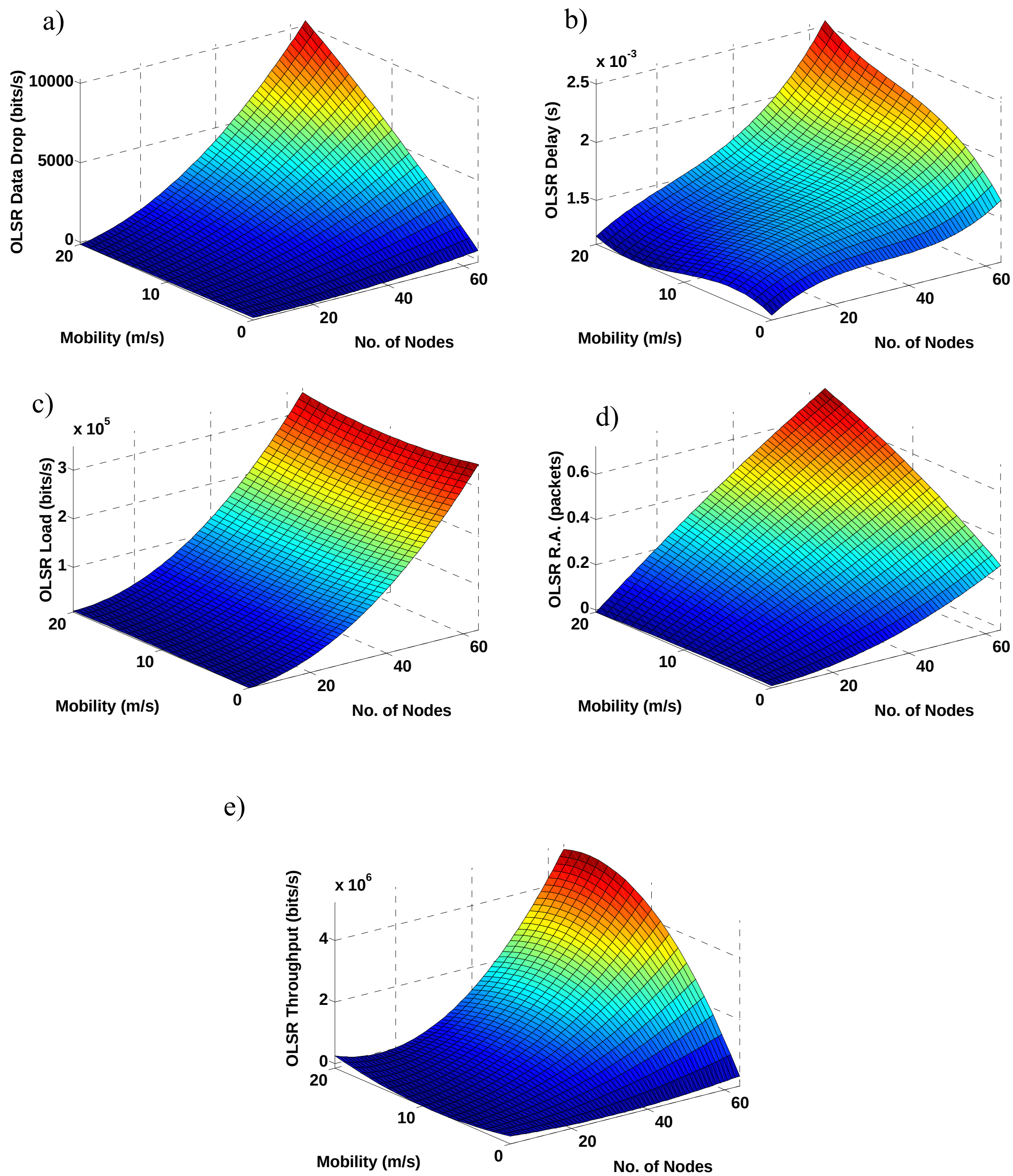

Figure 6.2: MANET output performance RE models using OLSR routing protocol.

The regression equations for DSR's: data drop, delay, load, and RA are cubic equations with second order interaction, whereas DSR's throughput regression equation is a square equation with second order interaction. These equations modelled the performance parameters for DSR, as shown in subfigures (a), (b), (c), (d), and (e) in Figure 6.3.

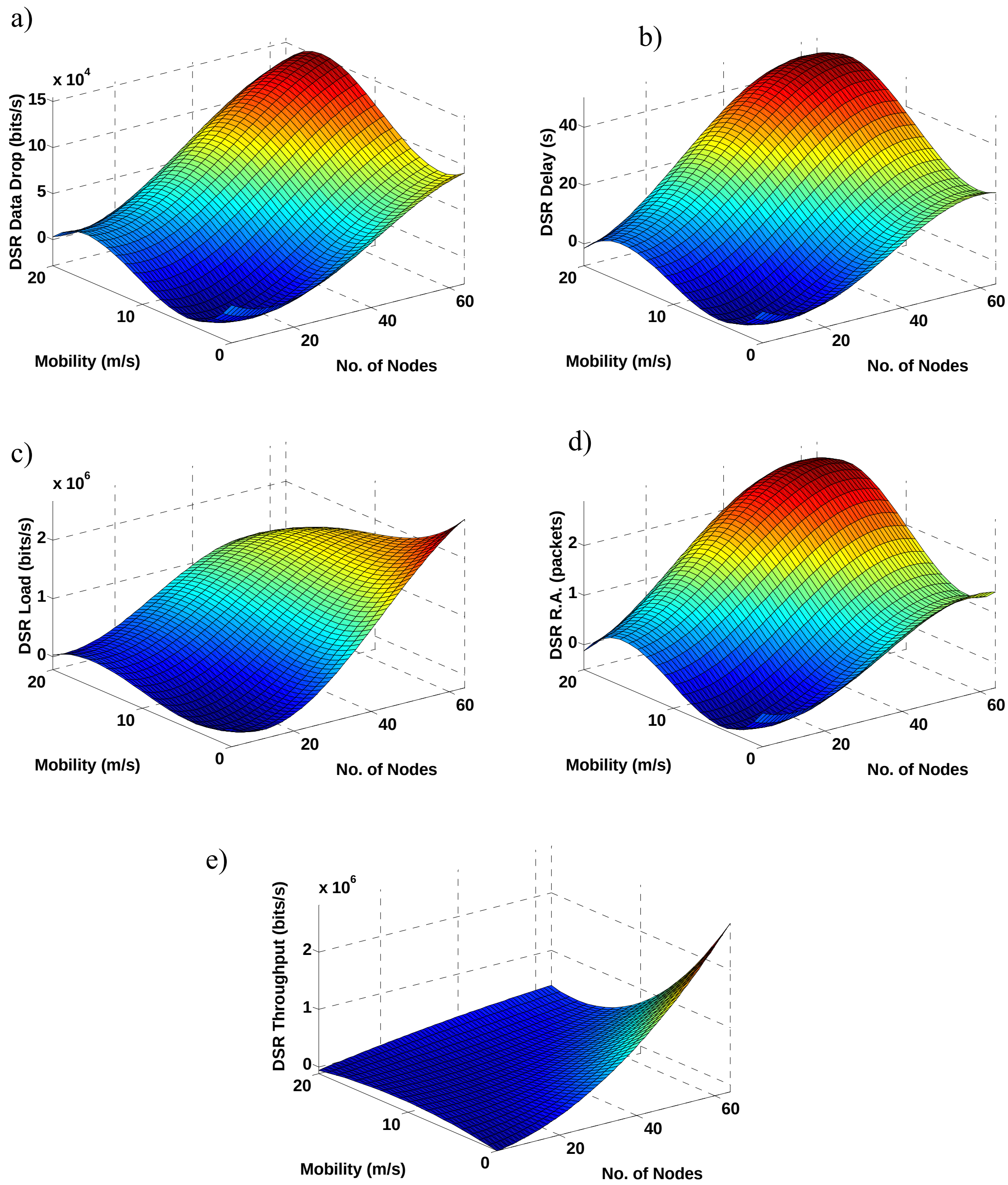

Figure 6.3: MANET output performance RE models using DSR routing protocol.

The regression equations for AODV's are cubic equations with second order interaction for data drop, delay, load, and throughput. These equations modelled the performance parameters for AODV, as shown in subfigures (a), (b), (c), (d), and (e) in Figure 6.4.

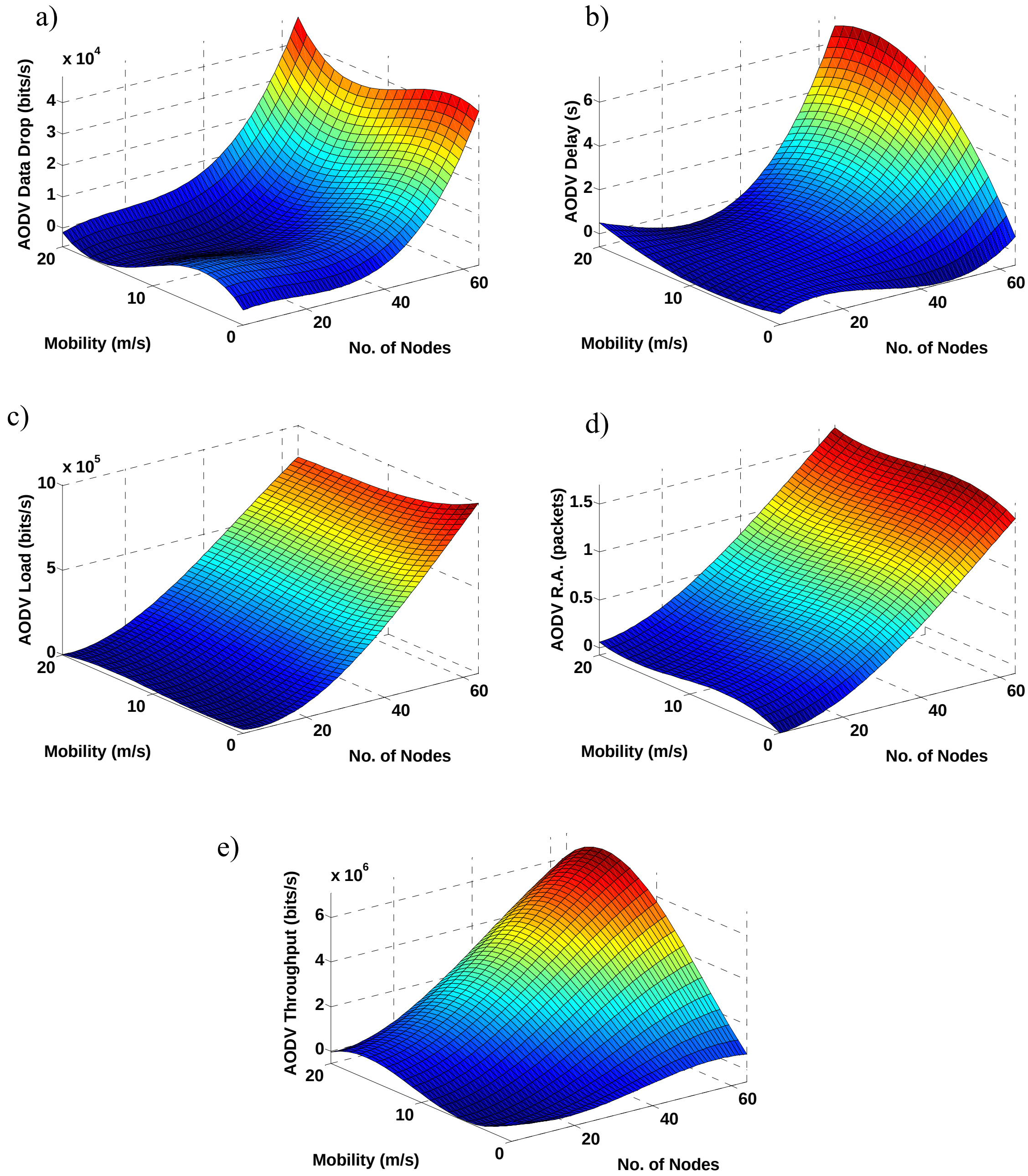

Figure 6.4: MANET output performance RE models using AODV routing protocol.

6.4.2 ANN MANET Models

MATLAB™ was used to program the neural network modular. The ANN modular is constructed as a feed-forwarded back-propagation network that is composed of three layers: input, hidden, and output, as illustrated in Figure 6.5.

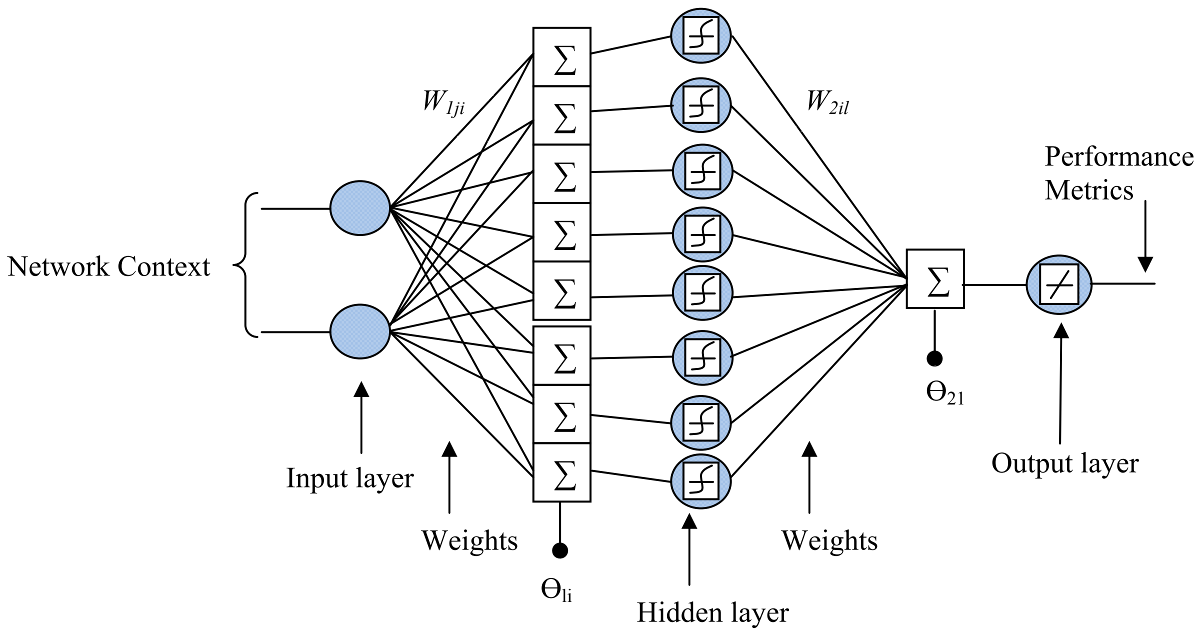

Figure 6.5: ANN MANET model.

The input layer consists of two neurons and the second hidden layer consists of eight neurons, while the third layer has one neuron. The hidden layer neurons use a hyperbolic tangent sigmoid function to calculate the layer's output, as shown in Equation (6.10). This transfer function is mathematically equivalent to the *tanh* function.

$$Tansig\,(n) = \frac{2}{(1+\exp(2n))^{-1}} \tag{6.10}$$

where n is define as

$$n = \sum_{j=1}^{k} w_{1ji} x_j + \theta_{1i} \tag{6.11}$$

where x_j is the input layer to node j; W_{1ji} is the weight between node j in the input layer and node i in the hidden layer; Θ_{1i} is the bias of node i in the hidden layer (it plays the role of an intercept in the linear regression); w_{2i1} is the weight between node i in the hidden layer and the node in the output layer; and Θ_{21} is the bias of the node in the output layer.

The output layer corresponds to the performance metric modelled, with a linear transfer function which is similar to Equations (6.7) and (6.8).

Thus, the predicted performance *y* given by the neural network model shown in Figure 6.5 could be expressed as follows:

$$y = purelin\ (\sum_{i=1}^{8} w_{2i1} \times Tansig\ (n) + \theta_{21}) \tag{6.12}$$

The ANN models were trained to simulate and present the MANET output performance behaviour each time for one of the three protocols (OLSR, DSR, and AODV). For each routing protocol, five ANN models were trained. Each model represents one of the five performance parameters against the network context; training was performed for 10 epochs. In total, 15 models were developed for the three protocols.

A well known fact is that ANNs suffer from overtraining problems as the network incorporates the inherent "noise" variation of a sample population. As such, MANET models were affected by and suffered from this problem in the training process. One of the solutions for this problem was the use of the ensemble modelling technique [22]. This technique was employed with MANET models by training different neural networks on the same MANET data set. The training generated 10 models in 10 sessions, with each training session resulting in a different model. After creating the 10 models, the set of the network context parameter for mobility was partitioned to create 30 values, starting from 0 (m/s) and ending in 20 (m/s), in the sequence: 0 (m/s), 0.1 (m/s), 0.2 (m/s), 0.3 (m/s),……, 0.9 (m/s), 1 (m/s), 2 (m/s), 3 (m/s),……9 (m/s), 10 (m/s), 11 (m/s), 12(m/s),…… 19 (m/s), and 20 (m/s); next, the new inputs for the mobility and the network size were entered to the 10 trained neural networks. It is an ensemble of these 10 models that will be used to create the most dominant MANET, as shown in subfigures (a), (b), (c), (d), and (e) in Figures 6.6, 6.7, and 6.8.

Comparing the MANET original performance models in Figures 5.6, 5.7, and 5.8 in Chapter 5 with ANN models, in spite of using the ensemble technique to solve the overtraining problem, some ANN models are not representative and corrupted. Specifically in Figure 6.7, the models in subfigures (b) and (d) are corrupted between mobility set 10 and 20, as well as in Figure 6.8 subfigure (b) in which the model is corrupted between mobility set 20 and 30.

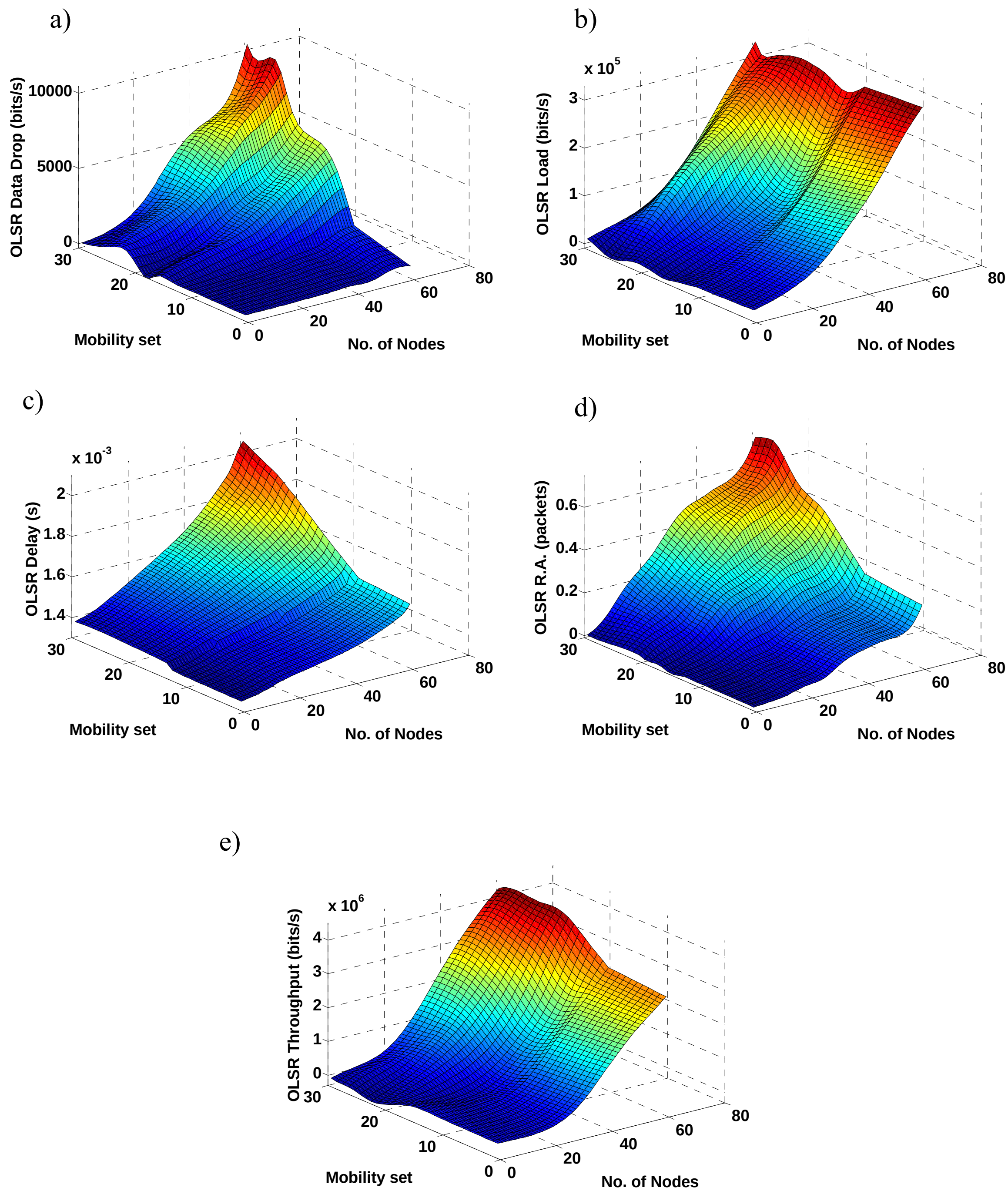

Figure 6.6: MANET output performance ANN models using OLSR routing protocol.

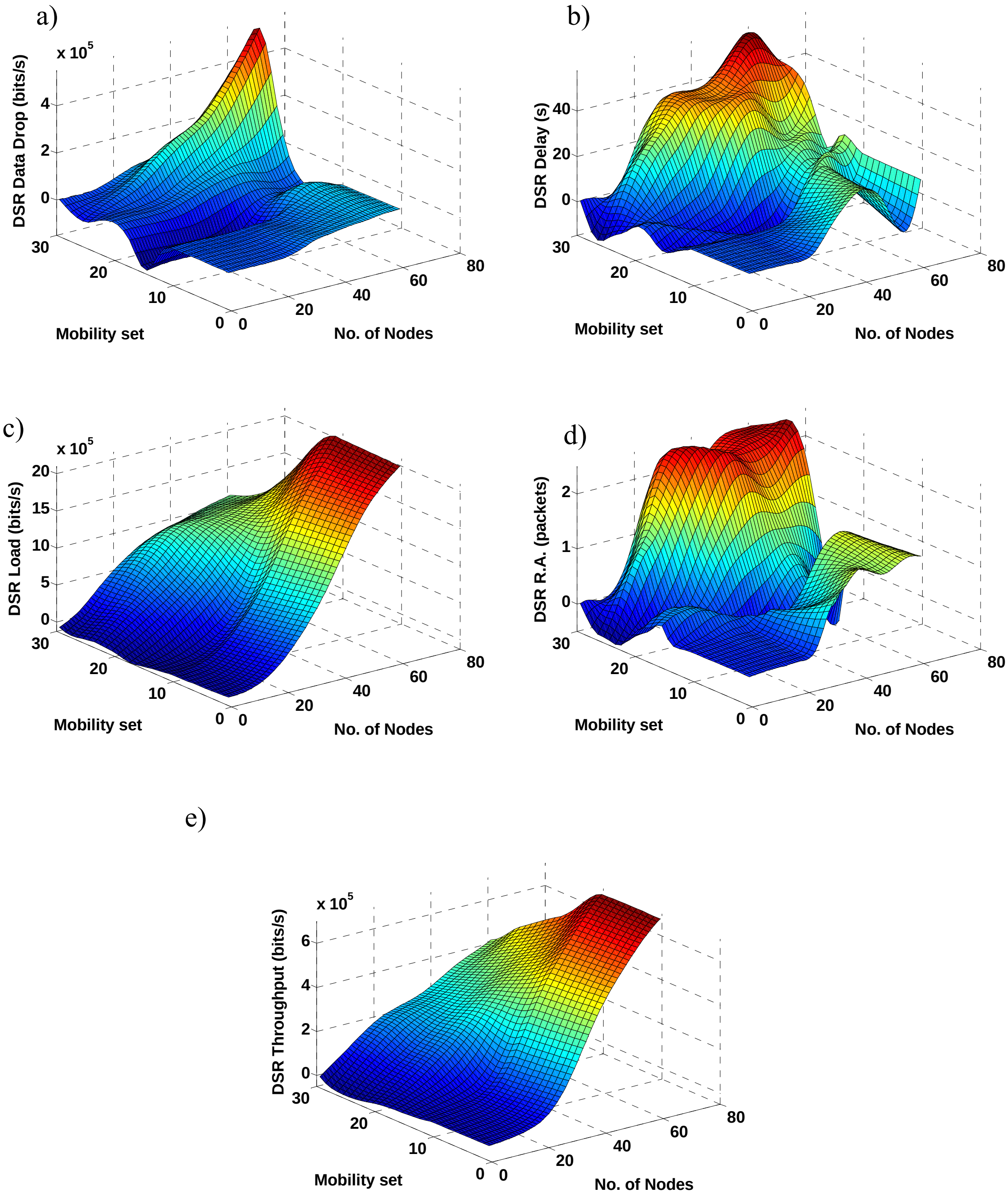

Figure 6.7: MANET output performance ANN models using DSR routing protocol.

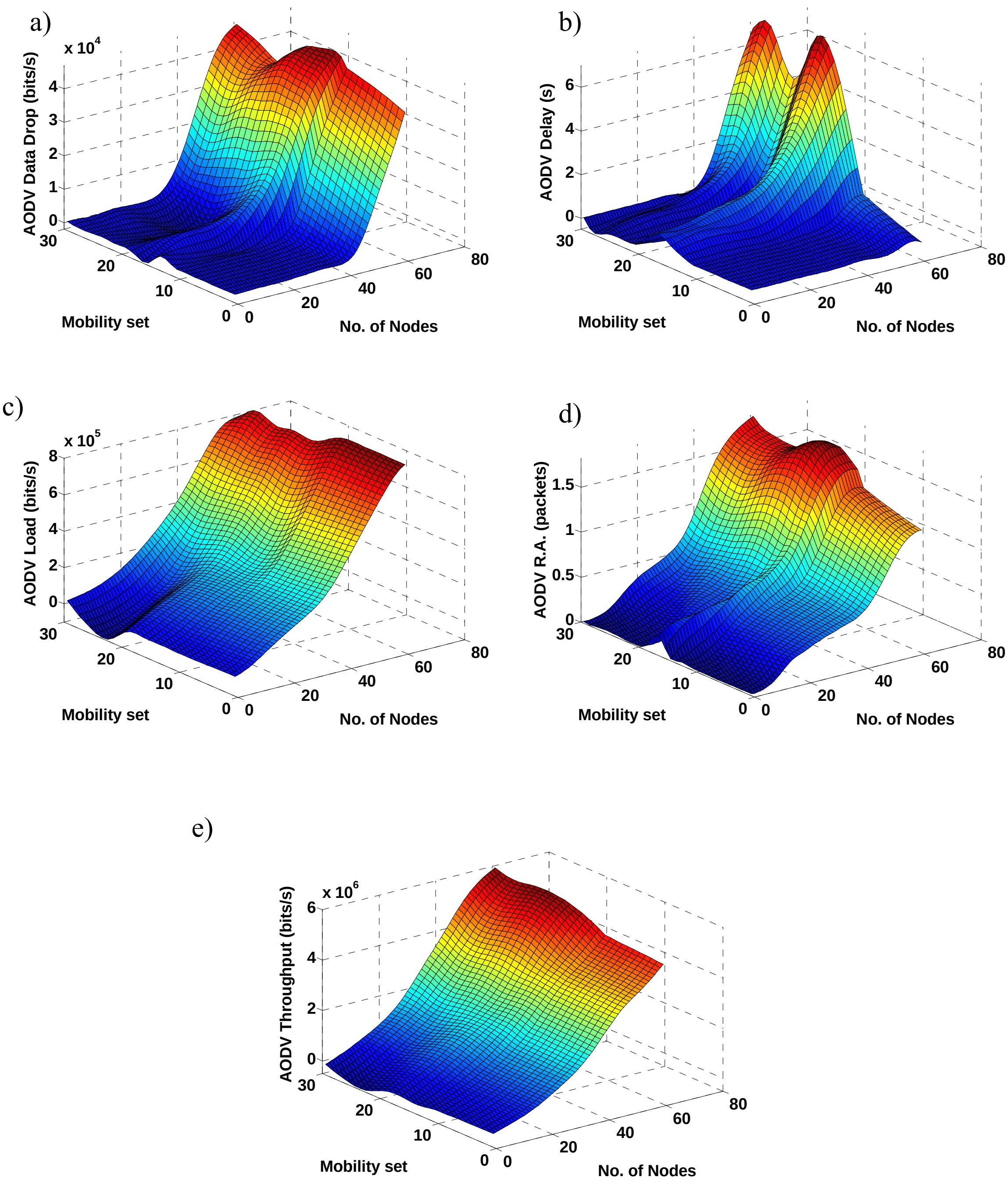

Figure 6.8: MANET output performance ANN models through operating AODV routing protocol.

6.4.3 NF MANET Models

MATLAB™ was utilised to develop MANET neuro-fuzzy models using the Fuzzy Logic Toolbox. All models were created using the ANFIS package. By using a hybrid learning procedure, ANFIS can construct an input-output mapping based on both human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs.

The model topology was based on the TSK type; two Gaussian membership functions for the two input variables. Depending on the data provided by the MANET Simulator, membership functions (*mfs*) and fuzzy rules are established to create 110 NF rules for the output parameters of the three protocols, as shown in Table 6.2.

Table 6.2: Performance's neuro-fuzzy membership functions and the three protocols' fuzzy rules.

Routing Protocol	Linguistic Labels	Data Drop	Retransmission Attempt	Throughput	Delay	Load
OLSR	*mf1* × *mf2*	3×2	3×2	3×3	3×2	3×3
	rules	6	6	9	6	9
DSR	*mf1* × *mf2*	2×2	2×2	2×2	2×2	2×2
	rules	4	4	4	4	4
AODV	*mf1* × *mf2*	3×3	4×3	4×3	3×3	4×3
	rules	9	12	12	9	12

If the output performance data suffers rapid changes, this will demand an increase in the number of membership functions. In contrast, if the performance data has smooth changes, the membership functions are needed less. In another words, when the number of membership functions increase, the rapid changes that occur in the model will be clearly reflected.

The number of rules will be affected too, as it is the product of multiplying the membership functions (*mf*s) of the input parameters as presented in Equation (6.5). Therefore, the increase in the *mf*s will also lead to an increase in the rules. For example, referring to Table 6.2, the AODV load model requires (4 *mf*s × 3 *mf*s). Accordingly, 12 fuzzy rules should be considered for the AODV load model, since the number of rules depends on the number of *mf*s. In contrast, all DSR performance models require (2 *mf*s × 2 *mf*s), which produce 4 fuzzy rules.

The rules and the weight for each input parameter will determine the final output model for each protocol performance, with each model represented by its own number of rules. The training was performed for three epochs. The MANET NF model's structures are the same as in Figure 6.1, the only difference is that MANET inputs parameters: A (no. of nodes) and B (mobility) not always converted into two objects, as they will converted to more than two objectives. Equations from (6.3) through (6.8) are implemented to create the NF model for each output performance parameter. For each routing protocol, five NF models were trained. In total, 15 models were developed for the three protocols.

The 3D shapes shown in subfigures (a), (b), (c), (d), and (e) in Figures 6.9, 6.10, and 6.11 present the NF models for each routing protocol. The models show how each protocol parameter responds with respect to the two context parameters as each subfigure represents data for a particular protocol performance. For example, subgroup figure (a) in Figure 6.11 represents AODV delay response relating to a mobility range of 0 to 20 (m/s) and network size varying between 4 and 64 nodes.

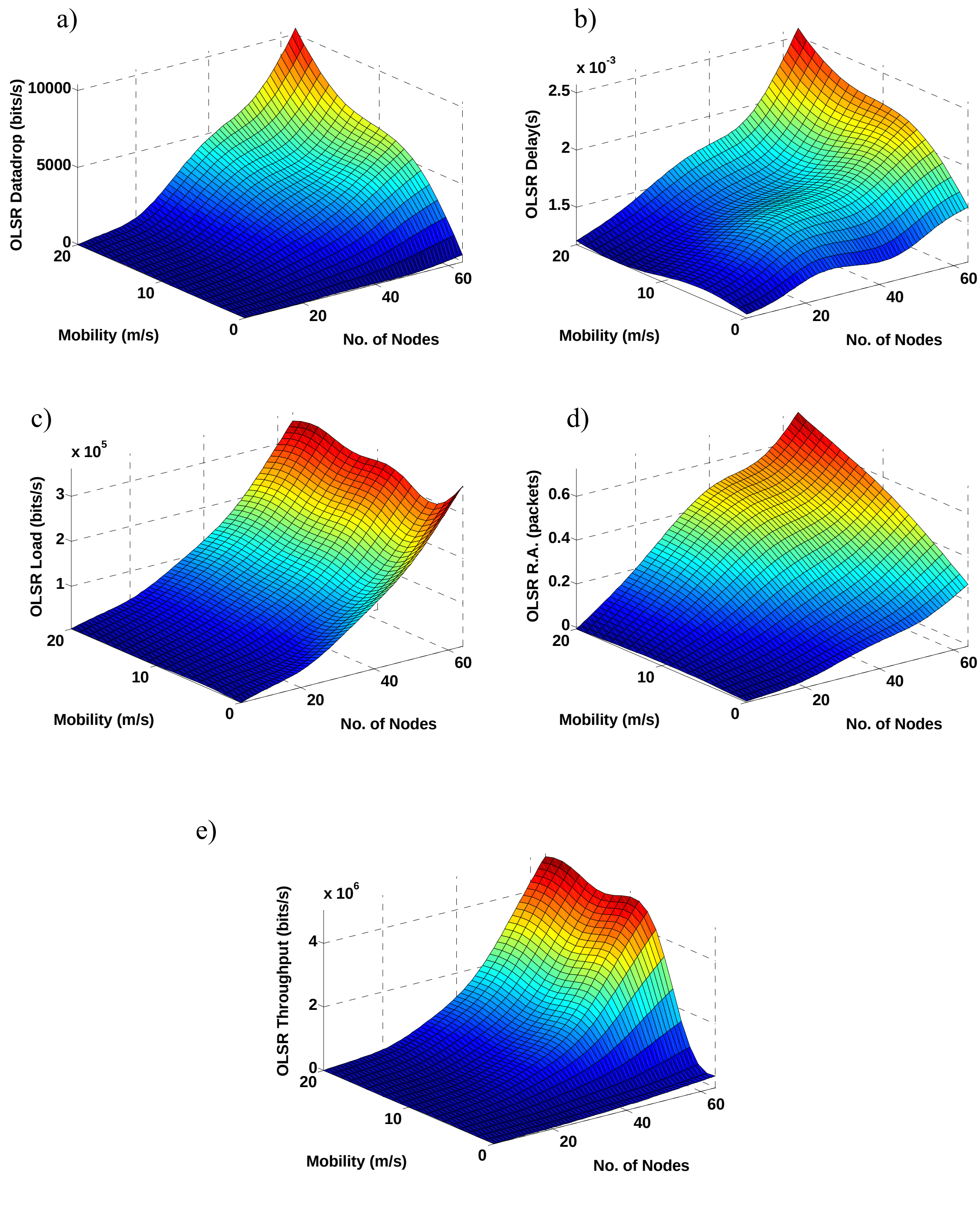

Figure 6.9: MANET output performance NF models using OLSR routing protocol.

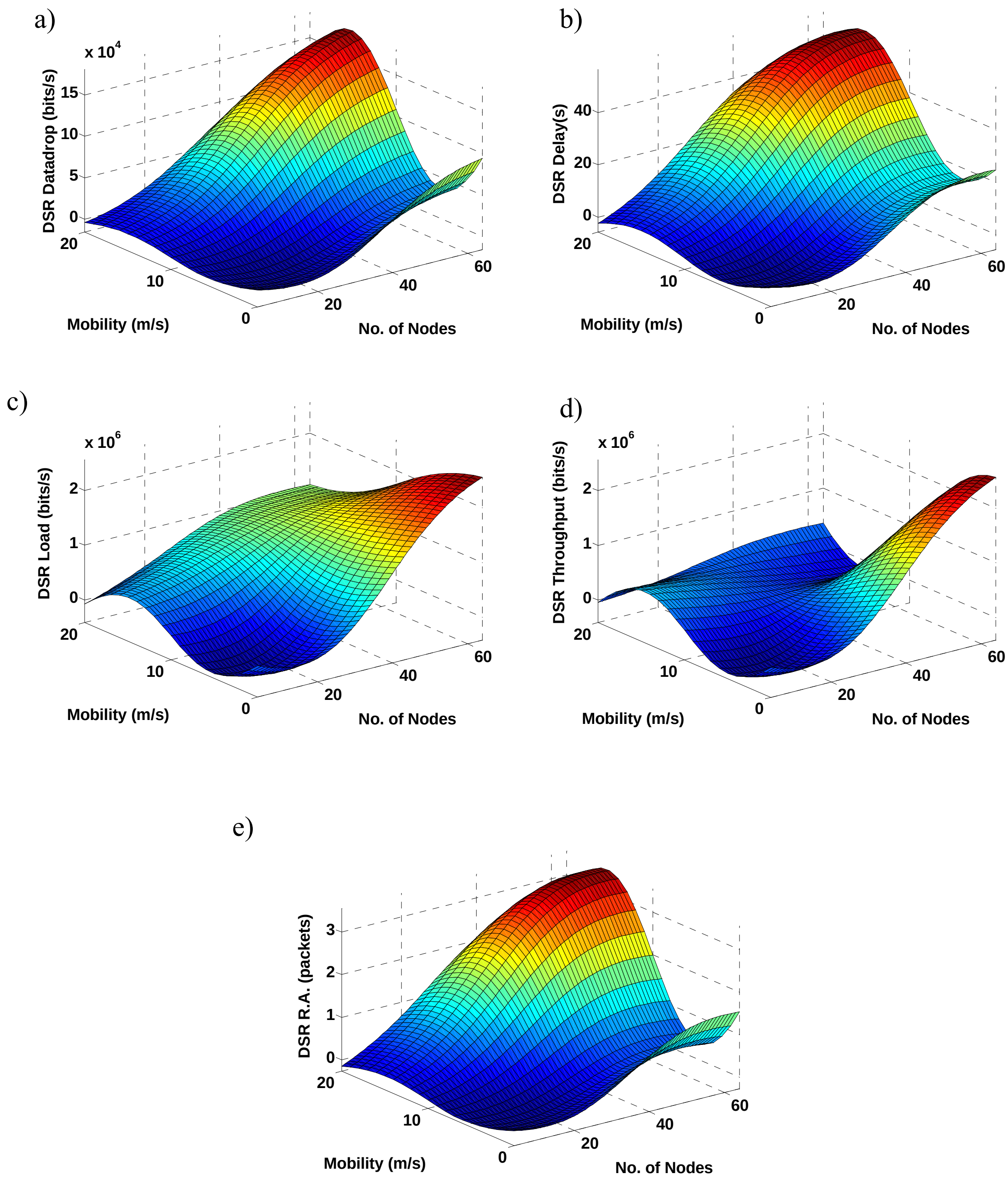

Figure 6.10: MANET output performance NF models using DSR routing protocol.

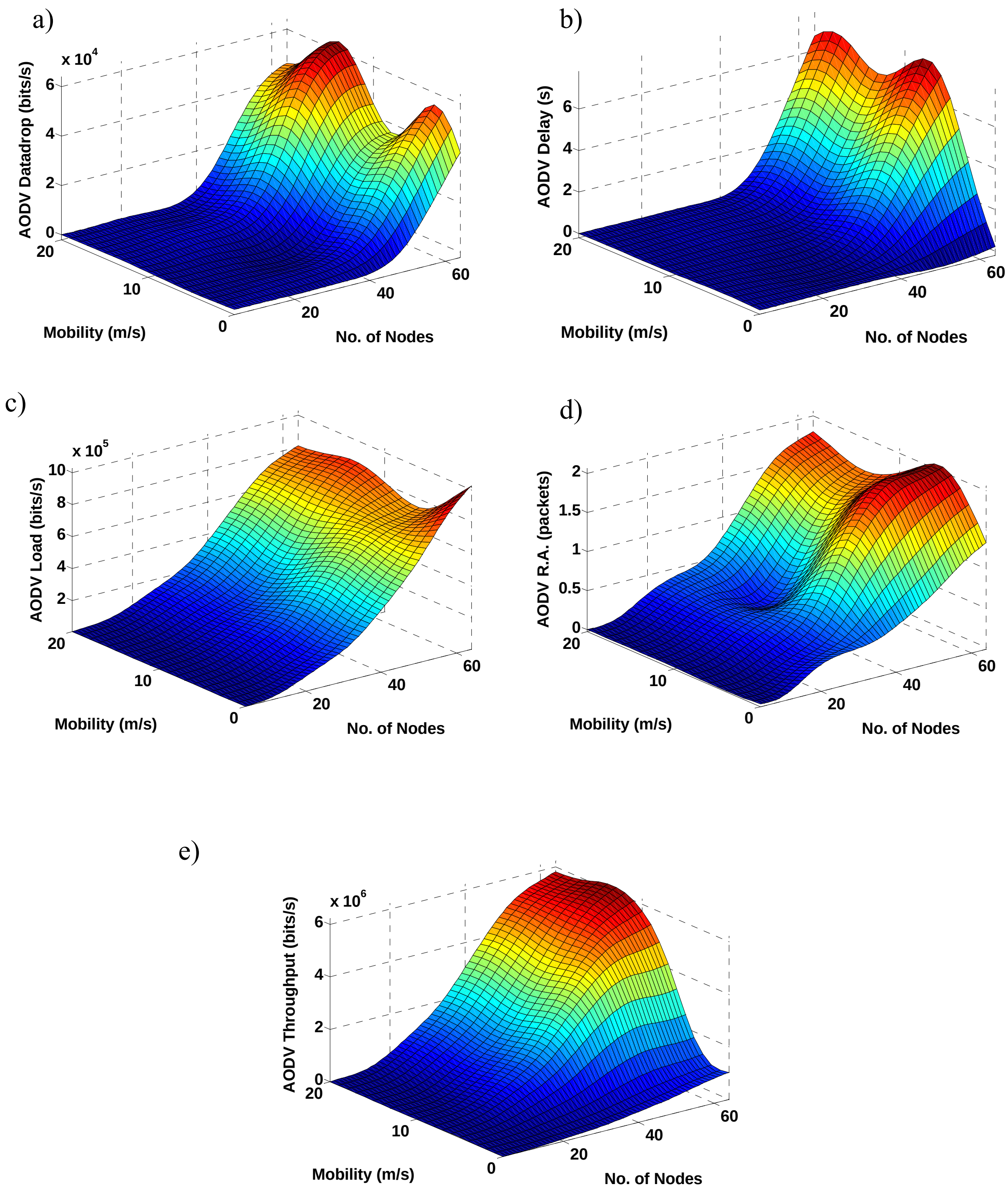

Figure 6.11: MANET output performance NF models using AODV routing protocol.

6.4.4 MANET Models Comparison

MANET performance models are very useful for prediction purposes and are helpful in the decision making process; the Optimiser proposed by this thesis will therefore rely on these models to predict the output performance for the system and then decide the optimum protocol. As such, the more accurate the models are, the more accurate the prediction obtained by the decision making process.

Therefore the results of the three different techniques: RE, ANN, and NF, respectively, and the MANET performance models in Figures 6.2 through 6.11 should be compared to first determine the best models and then select the best MANET modelling technique.

The regression models, in spite of having second and third order equations, fail to interpret the changes in the performance data in a representative curvy model, whereas AI (ANN or NF) models represent MANET performance more realistically. Comparing the AI models together, NF models are smoother, more efficient, and more accurate than ANN. To present a MANET parameter, ANN models bend and curve more than NF models through their training epochs (the overtraining problem corrupted the ANN models).

A quantitative analysis was performed to choose the best representative MANET models. For each output performance parameter, the Root Mean Square Error (RMSE) of the actual data ($D_{original}$) and the model data (D_{model}) was calculated, as defined in Equation (6.13):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (D_{Model} - D_{original})_i^2}{n}} \tag{6.13}$$

Tables 6.3, 6.4, and 6.5 present *RMSE* calculation results utilising RE, ANN, and NF for MANET employing OLSR, DSR, and ADOV routing protocols, respectively. For the four performance outputs delay, load, RA, and throughput, the RMSE of the NF models was the best. The conclusion drawn from the tables' results is that the NF models best represent MANET performance and therefore NF models will be helpful to the proposed system Optimiser.

Table 6.3: Root Mean Square Error for MANET output parameters utilising OLSR routing protocol.

RMSE	OLSR		
	RE	ANN	NF
Data Drop(bits/s)	161	35	31
Delay (s)	0.0000309	0.0000998	0.0000109
Load (bits/s)	6420	6540	1650
RA (packets)	0.0145	0.008	0.0034628
Throughput (bits/s)	185000	6530	246000

Table 6.4: Root Mean Square Error for MANET output parameters utilising DSR routing protocol.

RMSE	DSR		
	RE	ANN	NF
Data Drop(bits/s)	10200	7400	1890
Delay (s)	3.5906	3.4121	0.82681621
Load (bits/s)	215000	211000	195000
RA (packets)	0.1988	0.1831	0.03094911
Throughput (bits/s)	242000	192000	55200

Table 6.5: Root Mean Square Error for MANET output parameters utilising AODV routing protocol.

RMSE	AODV		
	RE	ANN	NF
Data Drop(bits/s)	2230	392	147
Delay (s)	0.3657	0.032	0.01020036
Load (bits/s)	17900	36200	1870
RA (packets)	0.1094	0.4414	0.00843813
Throughput (bits/s)	207000	250000	1270

6.5 Summary

The models created in this chapter employed two modelling approaches. The empirical approach was represented by regression equations and the AI approach was represented by artificial neural networks (ANN) and neuro-fuzzy (NF) networks. The models characterize each routing protocol, as each model represents the protocol's output parameter response and was trained to represent the network history, as well as predict the network performance behaviour for any network size from 4 to up to 64 nodes, and an average mobility from 0 (m/s) to up to 20 (m/s) (not merely the 7 levels of network size and the 4 levels of average mobility considered in Chapter 5).

In this chapter, a quantitative comparison of the MANET models created by the three modelling approaches (RE, ANN, and NF) was also undertaken to evaluate each model. This led to the conclusion that the NF technique is the best technique to represent MANET performance models that support the decision to choose the optimum routing protocol.

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Chapter 7

Intelligent Optimisation Techniques

7.1 Introduction

Heuristic methods are defined as the experience-based methods that help in problem solving, learning, and knowledge discovery [1]. Additionally, a *metaheuristic* algorithm is a set of algorithmic concepts that can be used to define heuristic methods applicable to a wide set of different problems. In another word, *metaheuristic* is a general-purpose algorithmic framework that can be applied to different optimisation problems with relatively few modifications [2]. Artificial intelligence (AI) techniques are *metaheuristic* methods, such as the ANN and NF mentioned in Chapter 6, as well as intelligent optimisation techniques.

In this chapter, two intelligent computation techniques, GA and PSO, have been emphasized. These AI techniques are defined and the main functions for each technique introduced. In this chapter, there are two main contributions; the first is employing two intelligent optimisation techniques as predictors to the MANET, and the second is selecting one of these techniques to be used as the Optimiser for the I-MAN optimisation system.

In Section 7.2, intelligent computing optimisation techniques are defined and then two main intelligent optimisation techniques, the Evolutionary Computation and Swarm Intelligence, explained. In Section 7.3, Genetic Algorithm (GA) is presented as an example of Evolutionary Computation whereas in Section 7.4, Particle Swarm Optimisation (PSO) is presented as an example of swarm intelligence. In Section 7.5, GA and PSO are briefly compared. In Section 7.6, network context cases and the Optimiser configurations are determined to implement with GA and PSO as the MANET Optimisers. This section also gives the module results for each Optimiser and evaluates them. The validation table confirmed the MANET routing problem mentioned in Section 1.2.2 by selecting different routing protocols for different context. The best Optimiser is then selected by comparing the Optimisers' best objective. Finally, Section 7.7 concludes the chapter with a summary.

7.2 Intelligent Computing Optimisation Methods

The intelligent optimisation techniques were implemented to solve complex problems on a realistic scale and yielded satisfactory results.

The calls by the Journal of Information Technology Research: Nature-inspired Computing and Applications classify the intelligence optimisation techniques under the following categories:

- Evolutionary Computation (comprising Genetic Algorithm)
- Swarm Intelligence Computing (comprising Particle swarm optimisation, Ant colony optimisation, Fish school search, and Artificial Bee Colony Algorithms)
- Others such as Weed invasion optimisation.

The emphasis of this chapter is on explaining and implementing Genetic Algorithm (GA), the most popular form of Evolutionary Computation [3]. Particle Swarm Optimisation (PSO) that represent Swarm Intelligence is also explained and implemented, as this technique demonstrated better results in a way faster and cheaper than other methods [4]. Therefore, the other optimisation techniques were not considered in this thesis.

7.2.1 Evolutionary Computation

Evolutionary Computation is the general term for several computational techniques that are based to some degree on the evolution of biological life in the natural world. Evolutionary Computation [5] uses an iterative process such as growth or development in a population. This population is then selected in a guided random search to achieve the desired end.

The common use of an Evolutionary Computation Algorithm (EA) requires four elements [6]:

A. An evaluation fitness function that determines the quality of any candidate solution in quantitative terms,

B. A representation or data structure that the computer uses to store solutions,

C. A random variation operator (or operators) that transforms “parents” into “offspring,” and

D. A mean of selecting the surviving solutions for the next generation.

In addition, the process must be initialized with a population of candidate solutions to the task at hand. This is often accomplished by seeding the first population with completely random solutions.

7.2.2 Swarm Intelligence

Swarm Intelligence (SI) is the property of a system whereby the collective behaviours of unsophisticated agents interacting locally with their environment cause coherent functional global patterns to emerge [7]. SI provides a base with which it is possible to explore collective (or distributed) problem solving without centralized control or the provision of a global model. SI evolution first searches the environment for good regions ,and after finding a good region of the search space, looks for the best point in that region [8].

7.3 Genetic Algorithm

Genetic Algorithm (GA) is an exploratory search and optimisation method that was devised based on the principles of natural biological evolution and population genetics [9]. As mentioned in the introduction, GA is a *metaheuristic* approach which does not require mathematical descriptions of the optimisation problem, but instead relies on the cost function in order to assess the fitness of a particular solution to the problem in question. GA, as such, is capable of providing a robust and efficient search in a complex space. The powerful ability of GA optimisation led to interest in its performance for global optimisation on a large scale.

The flowchart shown in Figure 7.1 illustrates the main operations of a GA in sequence.

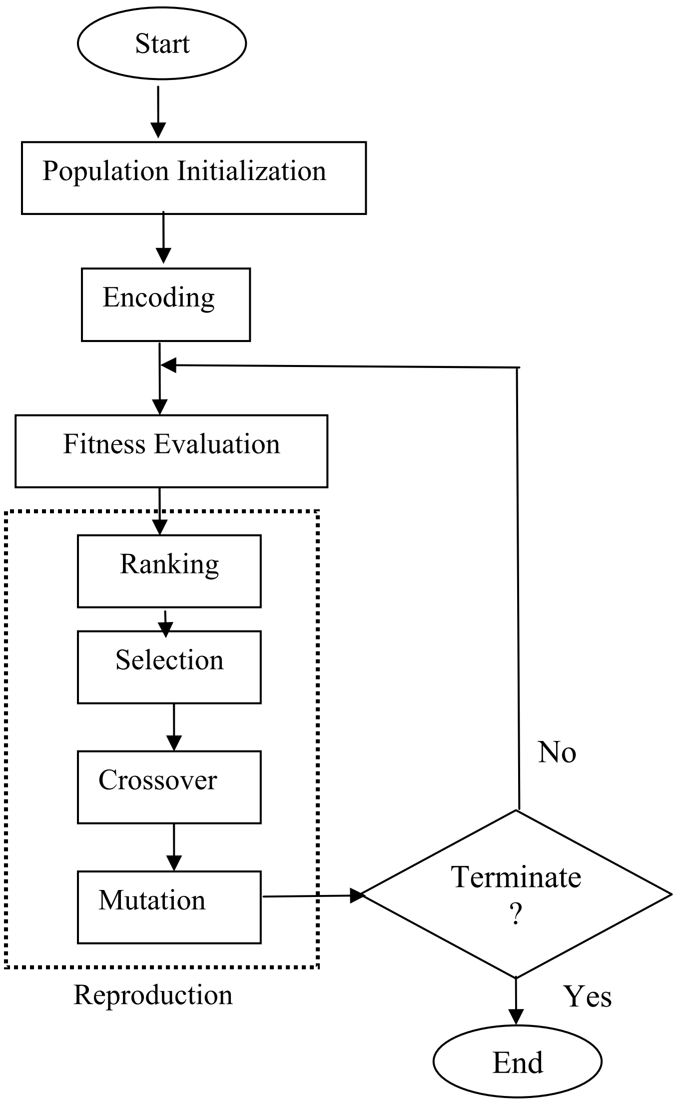
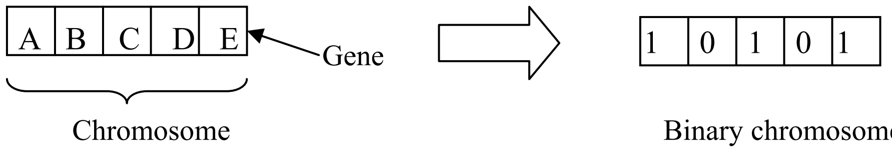


Figure 7.1: Typical Genetic Algorithm flowchart.

As shown in Figure 7.1, the GA procedure includes the following processes:

A. *Population initialization*: Possible solution candidates are initialized by randomly generating a population of individual chromosomes, with each representing a different solution to the problem. The population in each generation is determined by the number of chromosomes. The first column in Table 7.1 represents the chromosome population.

B. *Encoding*: In computer science, the problem is encoded into a set of strings (chromosomes) and each individual encoded into binary string that contains a well-defined number of bits (1's and 0's). An example of this is shown in Figure 7.2 (a), whereas a chromosome that is an array of genes converted into either 0s or 1s is shown in Figure 7.2 (b).



(a) Normal chromosome (b) GA chromosome

Figure 7.2: Chromosome presentation.

C. *Evaluation*: This process contains a predefined fitness function that evaluates each member of the population. A fitness value is assigned to determine how "good" each string is, as each string represent a solution. The higher the fitness value of an individual string, the higher its chance of survival and reproduction. The second column in Table 7.1 shows an example of fitness function results for a chromosome population, where the value for each function was selected randomly in order to explain the GA evaluation process. The third column in the figure represents the chromosome fitness evaluation level from (1-10), with the most fit chromosome scoring 10 and the least scoring 1.

Table 7.1: GA chromosome population, evaluation function and ranking processes.

Chromosome population	*Fitness function*	*Evaluation level*	*Ranking*
Chromosome 1	*f*(Chromosome 1) = 0.5	5	Chromosome 9
Chromosome 2	*f*(Chromosome 2) = 0.25	3	Chromosome 10
Chromosome 3	*f*(Chromosome 3) = 0.45	4	Chromosome 4
Chromosome 4	*f*(Chromosome 4) = 0.84	8	Chromosome 7
Chromosome 5	*f*(Chromosome 5) = 0.05	1	Chromosome 6
Chromosome 6	*f*(Chromosome 6) = 0.7	6	Chromosome 1
Chromosome 7	*f*(Chromosome 7) = 0.79	7	Chromosome 3
Chromosome 8	*f*(Chromosome 8) = 0.06	2	Chromosome 2
Chromosome 9	*f*(Chromosome 9) = 0.95	10	Chromosome 8
Chromosome 10	*f*(Chromosome 10) = 0.83	9	Chromosome 5

In the reproduction process, new offspring will be created through random variation; the reproduction consists of ranking, selection, crossover, and mutation.

D. *Ranking*: The fittest individuals are ranked according to their evaluation level, as shown in the fourth column in Table 7.1. This operation models the natural mechanism "survival of the fittest." Fitter solutions (individuals with a highest fitness value) survive and are copied into the next generation while the weak ones perish.

E. *Selection:* This process decides the chromosomes that will be forwarded to the next operation, or the crossover (see below). The two most popular selection methods are the *roulette wheel* and *tournament* selection methods.

In the *roulette wheel* method, a chromosome is selected randomly from the range (0 - 1). The roulette wheel contains the chromosome population (as shown in Figure 7.3), as each chromosome is represented by a slot. The slot width varies depending on the chromosome fitness function (the second column in Table 7.1), where the slot width increases with an increase in the chromosome fitness function. Therefore, the probability of "dropping the ball" for the chromosome with the highest fitness will, in this way, also be increased. This method was adopted in this chapter through implementing GA with MANET.

In the *tournament* method [10], a number of chromosomes are picked randomly from the population to form a "tournament" pool. The two chromosomes with the highest fitness functions are then selected from this tournament pool as parents.

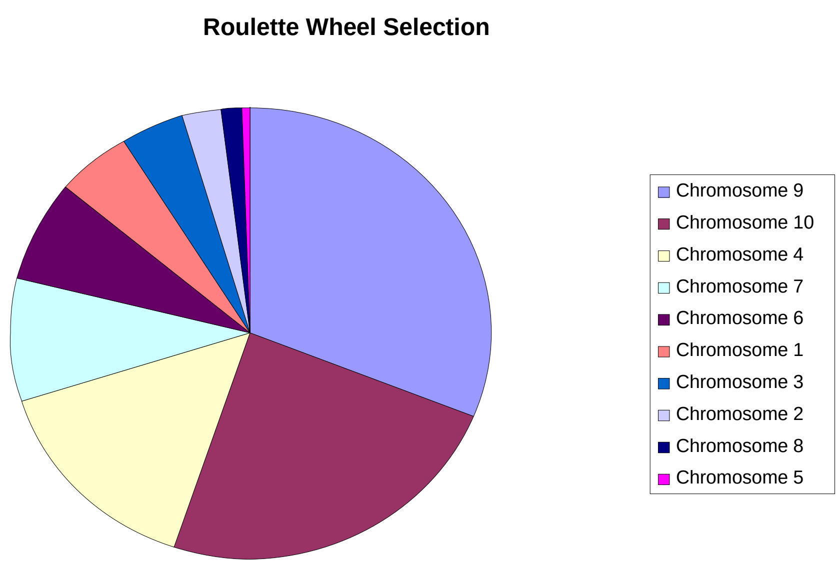


Figure 7.3: GA roulette wheel selection.

F. *Crossover*: In order to create a better population than the initial one, a mating process is carried out among the fittest individuals in the previous generation, since the relative fitness of each individual is used as a criterion for choice. Hence, the selected individuals are randomly combined in pairs to produce two offspring by *crossing over* parts of their chromosomes at a randomly chosen position of the string. These new offspring are supposed to present a better solution to the problem [11]. The three known crossover types, one-point, two-point, and uniform, are presented in Figure 7.4. In the one-point crossover (Figure 7.4 (a)), two parent strings are cut at the same point and offspring are formed by combining complementary genes from the parents. In two-point crossover (Figure 7.4 (b)), the two parents are cut at two points and offspring are formed by inserting a central sequence from the first parent into the second parent, and vice versa. Other types of crossover are possible, such as uniform crossover (Figure 7.4 (c)), in which offspring are generated by taking a certain number of genes from each parent, with no restriction on where these genes occur in the string.

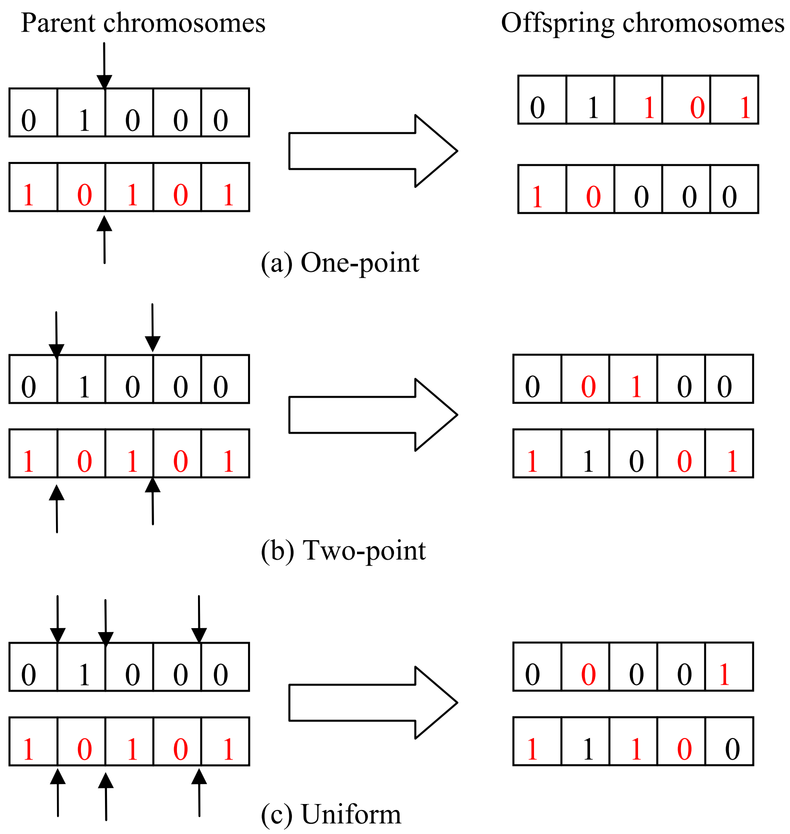


Figure 7.4: Genetic Algorithm crossover types: (a) One-point, (b) Two-point, and (c) Uniform.

G. *Mutation*: In order to provide extra excitation to the generation process, randomly chosen bits in the strings are inverted (0's to 1's and 1's to 0's), as shown in Figure 7.5. This mechanism is known as mutation and helps to speed up convergence by preventing the population from being dominated by the same individuals. A compromise, however, should be reached between too much or too little excitation by choosing a small probability of mutation.

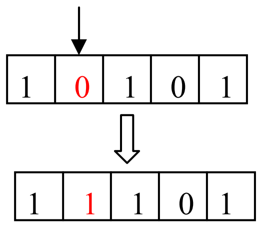


Figure 7.5: GA mutation.

The generational process is repeated until a termination condition has been reached. Common terminating conditions are listed below [12]:

- A solution is found that satisfies the minimum criteria;
- A fixed number of generations is reached;
- The allocated budget (computation time/money) is reached;
- The highest ranking solution's fitness has reached, or is reaching, a plateau such that successive iterations no longer produce better results;
- A manual inspection is performed; and
- Any combination of the above.

All in all, this ensures that the solution set is never empty.

In MANET, GA have been involve in solving route problems by selecting the shortest path [13] and developing optimised routing protocols such as [14] and [15]. Also, GA was combined with ANN, as in paper [16], for quick route rebuilding.

7.4 PSO Algorithm

Particle Swarm Optimisation (PSO) is a global optimisation technique that finds the best solution for the problem, presented as a point and a velocity. Based on certain metrics, each particle assigns a value to the position it has and also remembers the best position it has seen. The particle then communicates the best position to the other swarm members. Therefore, the particles will adjust their own positions and velocity based on this information. The communication can be common to the whole swarm, or be divided into local neighbourhoods of particles [17].

The general characteristics of particle swarm algorithm are as follows [18]:

One, PSO employs a *population* of particles.

Two, PSO has the "traditional" topology *gbest* and *pbest* to describe the interconnections among the particles. The *gbest* topology is considered the fully interconnected population as every member of the population can be influenced by every other member. In another words, the particles can be affected by the individual that has found the best solution so far. Therefore, the responsibility of *gbest* is ultimately to track the best solution found. The *pbest* topology is considered as a partially interconnected population in which every particle is connected to the neighbouring particles in the population array.

Three, every particle changes its position according to the change rule (known as position equation), as shown in Equation (7.2).

Four, as shown in Equation (7.1), the interaction rule (known as velocity equation) determines the next point of the particle which will be tested in the search space, wherein the particle's previous success in the search space, along with other particles' previous success, is considered .

Putting the previous characteristics in practice, Clerc and Kennedy [19] presented a simplified deterministic version of the particle swarm. As shown in Figure 7.6 and the flowchart in Figure 7.7 the particle's population is initialized with random positions *x(t)* and velocities *v(t),* and a cost function is evaluated using the particle's positional coordinates as input values. Positions and velocities [20] are adjusted with the function that evaluated the new coordinates at each time step, depending on Equations (7.1) and (7.2), respectively.

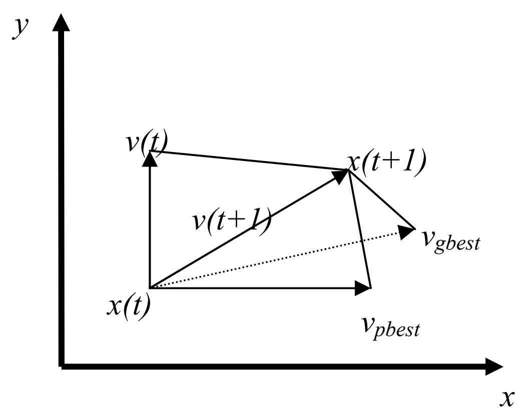


Figure 7.6: Concept of modification of a searching point by PSO.

When a particle discovers a pattern that is better than any it had previously found, it stores the coordinates in *pbest(t)*. The difference between *pbest* (the best point found so far) and the individual's current position is stochastically added to the current velocity, causing the trajectory to oscillate around that point. Further, each particle is defined within the context of a topological neighbourhood

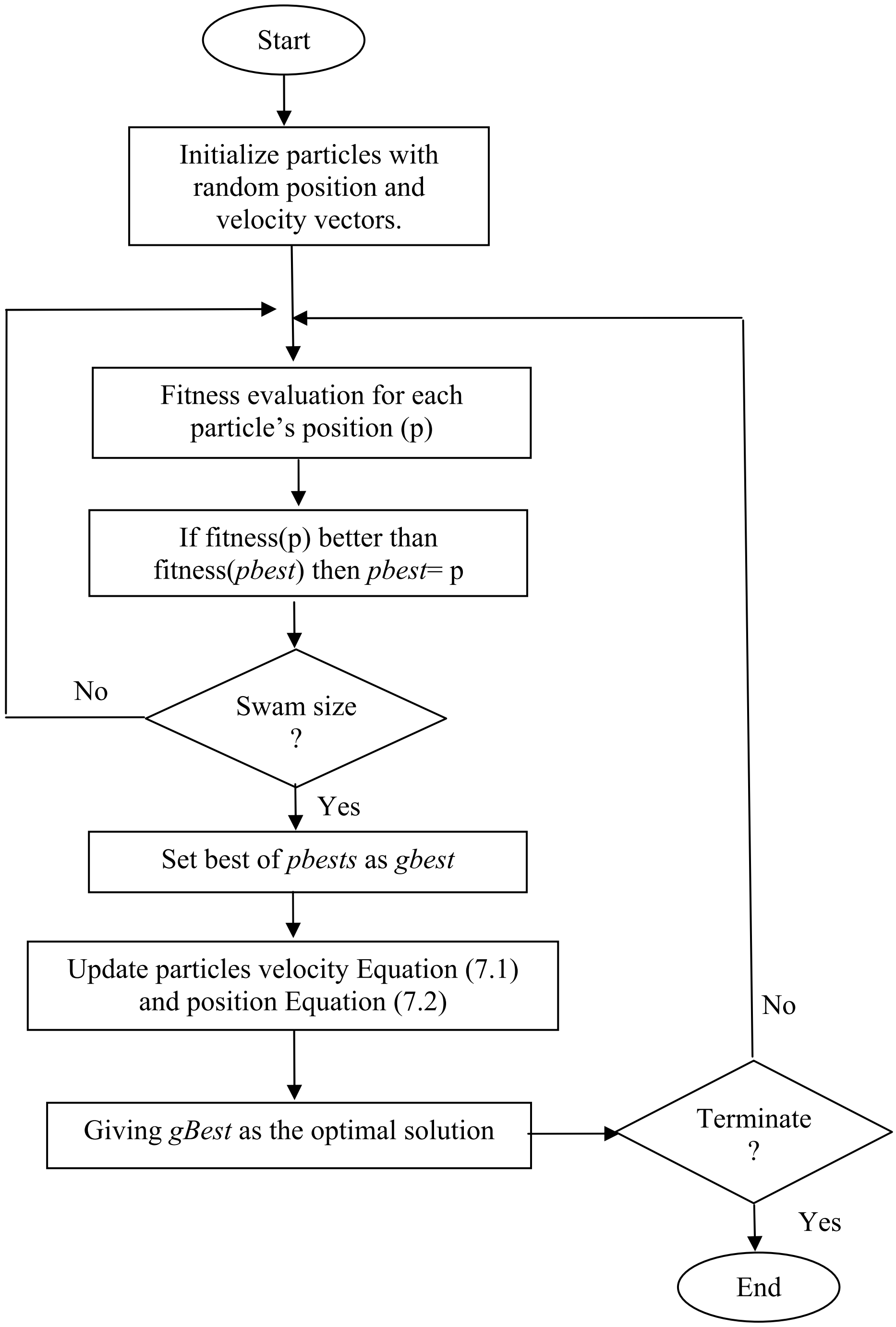


Figure 7.7: Typical flowchart for Particle Swarm Optimisation.

comprising itself and some other particles in the population. The stochastically weighted difference between the neighbourhood's best position *gbest(t)* and the individual's current position is also added to its velocity, adjusting it for the next time step. These adjustments to the particle's movement through space cause it to search around the two best positions, as shown in the equation below:

$$v(t+1) = wv(t) + \varphi_1 r_1 (pbest(t) - x(t)) + \varphi_2 r_2 (gbest(t) - x(t)) \tag{7.1}$$

where w is the inertia weight that can be either a constant or a value that changes linearly with the time; φ_1 and φ_2 are called "cognitive" and "social" parameters, respectively, and are random positive constants that weight the influence of the two different swarm memories; and $r1$ and $r2$ are random numbers between 0 and 1.

After the velocity vector had been calculated, the positions of the particles were updated according to the equation below:

$$x(t+1) = x(t) + v(t+1) \tag{7.2}$$

PSO was utilised in the Ad hoc network to satisfy some network requirements and develop routing protocol, as exemplified by papers [21] and [22]. Also, the PSO algorithm was involved in sensor networks to create energy-efficient networks, as in papers [23] and [24].

7.5 Comparison between GA and PSO

In this section, the main differences between the two investigated algorithms, GA and PSO, will be presented. While both algorithms use the fitness concept, they differ in other concepts that are listed in the table below.

Table 7.2: GA and PSO comparison.

	GA	*PSO*
1.	Implements the survival of the fittest	All its particles kept as members of the population through the course of the run
2.	Has selection operation	Has no selection operation
3.	Has crossover algorithm	The adjustment toward the best *p(t)* and *g(t)*
4.	Has mutation algorithm	Balance is achieved through the inertial weight factor (w)

7.6 Intelligent MANET Optimisation

In contrast to the traditional problem solving techniques [6], the *metaheurstic* algorithms are often much faster and more adaptable to changes in the environment because the knowledge regarding how to solve a problem is contained in the collection of individual solutions that has survived up to that point. This important characteristic has led to the utilisation of the evolutionary algorithms in MANET routing protocol optimisation.

In this thesis, the GA and PSO *metaheurstic* optimisation techniques are employed to search for the best fitted parameters for the proposed intelligent system; the Optimiser compares and evaluates the performance of the routing protocol in operation with the performance of other protocols in the same network context.

7.6.1 Determined the Network Context Cases

Before examining the two algorithms as Optimisers, a validation case (Table 7.3) was constructed to contain all the possible cases for the two input contexts, network size and average mobility. For example, Case 1 has a large and fast network, whereas Case 9 has a small and slow network.

Table 7.3: Validation cases.

Case no.	Network size	Average mobility (m/s)
Case 1	Large	Fast
Case 2	Large	Medium speed
Case 3	Large	Slow
Case 4	Medium	Fast
Case 5	Medium	Medium speed
Case 6	Medium	Slow
Case 7	Small	Fast
Case 8	Small	Medium speed
Case 9	Small	Slow

To convert the label of the network sizes (large, medium, and small) and average mobility (fast, medium, and slow speed) into quantitative values, each context parameter was classified into three fields, as shown in Table 7.4 for the network size and Table 7.5 for the average mobility. The data collected for the network size started from a lower limit of 4 nodes and ended up with an upper limit of 64 nodes, whereas the data collected for the average mobility started from 0 (m/s) and ended up with 20 (m/s).

The row (From - to) in Table 7.4 classified MANET by the following size criteria:

A small network: 4 nodes ≤ small network ≤ 17 nodes

A medium-sized network: 18 nodes ≤ medium network ≤ 36 nodes

A large network: 37 nodes ≤ large network ≤ 64 nodes.

Table 7.4: Network size classifications.

Network size	Small	Medium	Large
From - to	4 - 17	18 - 36	37 - 64
The cases studied	8	20	62

The row (From - to) in Table 7.5 classified MANET by the following mobility criteria:

A slow network: 0 (m/s) ≤ slow network ≤ 6 (m/s)

A network with medium speed: 6 (m/s) ≤ medium speed network ≤ 13 (m/s).

A fast network: 20 (m/s) ≤ fast network ≤ 13 (m/s).

Table 7.5: Average mobility classifications.

Mobility (m/s)	Slow	Medium	Fast
From - to	0 - 6	6.1 - 13	13.1 - 20
The cases studied	3	11	18

Then, for each classification field (column), one value is randomly selected to represent the field, as shown by the last rows in Tables 7.4 and 7.5. For example, number 8 selected randomly from the range (4 nodes ≤ small network ≤ 17 nodes) to present a small network. Therefore, the numbers in the second rows of Tables 7.4 and 7.5 will replace the labels in Table 7.3 to represent the network context that will be considered by the GA and PSO Optimisers. The final values are presented in the second and third columns of the validation table for each Optimiser in Tables 7.6 and 7.7.

7.6.2 The Optimisers Configurations

The two algorithms GA and PSO were employed as MANET Optimisers to find and select the optimum routing protocol based on the output performance. Both GA and PSO Optimisers were programmed in MATLAB^{TM}.

The NF models were supplied to both Optimisers; where each output parameter was modelled separately against the input parameters, each Optimiser normalizes the five performance parameters then merges them into one equation (cost function), and performs calculations for this equation in both Optimisers. There are many methods [25] to implement a parameter's normalization; the selected method depends on the available and known data. Thus, for the normalization in this thesis, the parameters depend on the equation below, as the maximum and the minimum values are known for each parameter:

$$\text{Normalized performance parameter} = \frac{parameter - parameter_{\min}}{parameter_{\max} - parameter_{\min}} \tag{7.3}$$

The cost function is the Mean Square (MS) of the normalized performance parameter, as shown below:

$$\text{Cost function} = \frac{(RA)^2 + (Datadrop)^2 + (Load)^2 + (Delay)^2 + (1 - Throughput)^2}{5} \tag{7.4}$$

From the Optimiser's decision it can be concluded that, depending on the cost function, it will select the routing protocol with the minimum MS to be the optimum routing protocol for that iteration. For each iteration (or generation) this selection process will be repeated.

The GA and the PSO optimisation process will result in a number of solutions equal to the iteration or the generation number. The selected solution, that is the optimum routing protocol, will be the one with the best objective (the minimum MS).

7.6.3 MANET Optimisation

Each Optimiser needs to be supplied with two inputs; the network size and the nodes average mobility to start its computing. Nine cases were studied based on Table 7.3, as in each case the inputs selected depended on the second rows of Tables 7.4 and 7.5.

7.6.3.1 GA MANET Optimiser

The GA Optimiser will base its decision on the outputs of the neuro-fuzzy models to find the optimum protocol that must be adopted. The GA was set with 3 bits of chromosome length for the three parameters (network size, average mobility, and protocol's name), with the chromosome value randomly selected between 0 and 250 and then converted to binary. The population size was 10 with average ranking, the mutation was 0.06, and the crossover probability was 0.95. Finally, the GA went through 12 generations to find the optimal solution. Table 7.6 shows the GA's optimum routing protocol solution for each case, the solution best objective amplitude, and the generation number for that solution.

Table 7.6: Genetic Algorithm module results.

Case no.	GA inputs		GA outputs		
	Network size	**Average mobility (m/s)**	**Routing protocol**	**Best objective**	**Generation no.**
case 1	62	18	AODV	0.5288	10
case 2	62	11	OLSR	0.4874	11
case 3	62	3	OLSR	0.9596	10
case 4	20	18	AODV	0.976	1
case 5	20	11	DSR	1.0959	1
case 6	20	3	DSR	1.0035	1
case 7	8	18	AODV	0.9983	8
case 8	8	11	AODV	1.0718	1
case 9	8	3	DSR	0.9981	10

The Pseudo-code for MANET GA is shown in Figure 7.8.

```
1. Generate initial population of chromosomes of size 10:x1,x2,x3...,x10
2.  Repeat
3.  Calculate the fitness of each chromosome: f(x1), f(x2),..., f(x10)
4.  Evaluate the individual fitnesses of the population.
5.  Select pairs of average-ranking individuals to reproduce.
6.   Select a pair of chromosomes for the crossover and the mutation.
7.   process.
8.   Change the genes values to the offspring chromosomes.
9.  Place the resulting chromosomes in the new population.
10.   If the size of the new generation is not equal to 10 go to 3
11.   Replace the current chromosome population with the new population.
12. Until terminating condition
```

Figure 7.8: MANET GA pseudo-code.

7.6.3.2 PSO MANET Optimiser

The PSO Optimiser was set with three-dimension swarm; the dimensions represent the inputs (network size, average mobility, and protocol’s name). The size of the swarm was 10, which was iterated 10 times; the error accepted was set to be less than 1×10^{-10}. The PSO Optimiser used the practical swarm optimisation for the velocity and the position equations, as in Equations (7.1) and (7.2). The Pseudo-code for MANET PSO is shown in Figure 7.9.

```
Initialize the three dimensions swarm,
 Do:
  For each particle:
   Calculate fitness value,
   If the fitness value is better than the best fitness value
    (pbest) in history,
    Set current value as the new pbest,
  End
  Find in the best pbest
  Set best pbest as the new gbest,
  Calculate particle velocity according to the velocity equation
  Update particle position according to the position equation
While maximum iterations not equal to 10 or minimum accepted error
  is not less than 1×10^-10.
```

Figure 7.9: MANET PSO Pseudo-codes.

The optimum routing protocol selected by PSO with its best objective and its iteration number is shown in Table 7.7.

Table 7.7: Practical Swarm Optimisation module results.

Case no.	PSO inputs		PSO outputs		
	Network size	**Average mobility (m/s)**	**Routing protocol**	**Best objective**	**Iteration no.**
case 1	62	18	AODV	0.324004	7
case 2	62	11	OLSR	0.323958	1
case 3	62	3	OLSR	0.323958	5
case 4	20	18	AODV	0.324002	8
case 5	20	11	DSR	0.323958	9
case 6	20	3	DSR	0.323962	1
case 7	8	18	AODV	0.518232	5
case 8	8	11	AODV	0.570085	6
case 9	8	3	DSR	0.323977	7

7.6.4 Creating the Validation Table

Tables 7.6 and 7.7 show that GA and PSO Optimisers chose the same routing protocols for the same cases, but most importantly, that the tables' results confirm that the Optimisers select different routing protocols through different cases.

To illustrate the point of view that an optimum routing protocol for a MANET context cannot be the same as for another context, and to demonstrate a possible scenario that could happen in MANET, a new validation table (Table 7.8) was established which listed all the possible changes to the two network context parameters for network size and average mobility.

Table 7.8: The validation table: Optimiser selection depending on input context.

First context		**Optimiser output**	**Second context**		**Optimiser output**
Network size	**Average mobility (m/s)**	**Routing protocol**	**Network size**	**Average mobility (m/s)**	**Routing protocol**
62	18	AODV	62	3	OLSR
62	18	AODV	8	18	AODV
62	18	AODV	8	3	DSR
62	18	AODV	62	11	OLSR
62	18	AODV	20	18	AODV
62	18	AODV	20	11	DSR
8	3	DSR	8	11	AODV
8	3	DSR	20	3	DSR
8	3	DSR	20	11	DSR
8	3	DSR	8	18	AODV
8	3	DSR	62	3	OLSR
8	3	DSR	62	18	AODV
20	11	DSR	20	3	DSR
20	11	DSR	8	11	AODV
20	11	DSR	8	3	DSR
20	11	DSR	20	18	AODV
20	11	DSR	62	11	OLSR
20	11	DSR	62	18	AODV

Table 7.8 includes the solutions for the Optimisers (GA or PSO as they select the same solution). After supplying the Optimiser with the first context, it will choose a solution that is most of the time different than its solution for the second context. The table shows the selection of different routing protocol depending on the input context. Table 7.8 has two main columns: the first main column for the first input context and the Optimiser selected routing protocol, and the second main column for the second input context and the Optimiser selected routing protocol. For example, for network with 62 nodes and 18 m/s average mobility the routing protocol selected was AODV, but when the context changes and the network average mobility is reduced to 3 m/s, OLSR is selected as the optimum routing protocol.

7.6.5 MANET Optimisers Selection

The GA Optimiser characteristic will be compared with the PSO Optimiser characteristic, based on Clerc and Kennedy statement about PSO [18] which says, "*Particle swarm optimisation comprises a very simple concept and paradigms; it can be implemented in a few lines of computer code. It requires only primitive mathematical operators, and is computationally inexpensive in terms of both memory requirements and speed* [19]."

a. GA is more complicated than PSO and includes many algorithms for encoding, ranking, cross over, and mutation. PSO is much simpler than GA as PSO computation relies on two basic equations.

b. GA requires more time in the computation process because of the number of algorithms to be processed. As such, few PSO computer codes can make the PSO Optimiser faster than the GA Optimiser at finding the solutions.

Comparing the efficiency of the two techniques quantitatively, the best objective in each of the fifth column of Tables 7.6 and 7.7 were studied. After examining the two columns, it shows that, in general, the GA best objective was always higher in value than the PSO best objective. For example, in Case 9, when network size was 8 nodes with average mobility 3 m/s, the routing protocol selected was DSR with GA best objective = 0.9981 and PSO best objective = 0.323977. This clearly shows that PSO have the minimum MS.

These comparison results evaluate each Optimiser; on this basis, a decision made to implement PSO techniques as an Optimiser in the I-MAN routing protocols optimisation system.

7.7 Summary

In this chapter, the necessity of utilising the Artificial Intelligence (AI) algorithms for optimizing MANET has been highlighted because of the AI's ability to adapt to changes in the environment and its algorithms' fast convergence. In this chapter, the sequence operations for each GA and PSO technique were also explained in detail. Furthermore, two MANET Optimisers were created: one with GA and the second with PSO. The results show that both Optimisers selected the same routing protocols for the same specified context.

Subsequently, a validation table was created to include all possible context changes. The results in the table clearly show that the Optimiser selects a different routing protocol in different cases. Also, the validation table results confirm that the changes in the network context will affect the network performance; therefore, for a better network performance, the Optimiser will select a different routing protocol if the context changes. Having evaluated the two Optimisers in this chapter, it was concluded that the PSO optimisation technique will be the optimisation technique used in the I-MAN routing protocols optimisation system.

7.8 References

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Chapter 8

System Implementation

8.1 Introduction

The focus in this chapter will be on implementing the intelligent system design outlined in Chapter 4. To create a MANET network with an embedded system, many modifications to the original nodes should be made. Therefore, the main contributions in this chapter are as follows:

1. Embedding the intelligent system in the Opnet^{TM}14 modeller.

2. Implementing the I-MAN routing protocols optimisation system in a case study. The case study scenario includes important changes in the network context; the use of complicated scenario such as this is of itself novel to this work, since to our knowledge there has been no simulation scenario which presents various context changes through one scenario.

3. Evaluating the proposed system by comparing networks operating with and without the intelligent system, as the performance results are the factors used to evaluate the networks.

The rest of the chapter is organised in the following manner: in Section 8.2, the structure for the network that utilises the intelligent system is determined; in Section 8.3, the implementation process for the I-MAN optimisation system in MANET is described in detail, which includes determining the role for each I-MAN system's component and the sequence for their operation; in Section 8.4, the modification to MANET's nodes that enables the intelligent system to function will be explained; and in Section 8.5, the I-MAN routing protocols optimisation system is tested by the simulation through a case study that includes different changes in the simulation environment, with the simulation results of the case study reviewed in this section as well. In Section 8.6, the results are compared and analysed whereas in Section 8.7 the network cost minimisation function is discussed. In Section 8.8, the network's performance is evaluated quantitatively. In Section 8.9, the effect of the Inter-Arrival Time (T_{IA}) on the performance is investigated. Section 8.10 presents the system limitations and finally, Section 8.11 illustrates the chapter findings.

8.2 I-MAN Optimisation System with MANET

A decision should be made about two important queries before implementing the intelligent system in a wireless MANET environment; these queries are twofold:

1. The need for the intelligent unit to be in decision node, and
2. The need for embedding the intelligent unit in all MANET nodes.

The forthcoming sections will discuss and clarify these two issues and then come to a decision as to what the network will be based on in the implementation stage.

8.2.1 Optimisation Unit in Intelligent Node

Obviously, the Ad hoc network depends on one routing protocol to route the packets from source to destination; this means that all Ad hoc nodes should share the same routing protocol at once (except the zone protocols). Therefore, deciding the optimum routing protocol is not an individual node's task that could be concluded independently from other nodes, as each node cannot decide its operating routing protocol without considering and referring to the other network nodes.

Therefore, referring the routing protocol decision to one intelligent node is crucial, as it should have a good knowledge about the network. Thus, in this research, the responsibility of deciding on the one suggested routing protocol is to be undertaken by a single node. After consulting all other network nodes, the node will then command the network to operate on a specific protocol. An intelligent module would be embedded in the decision node (optimisation unit), to support the node's decision regarding the optimised routing protocol selection. This node will be called the "Intelligent node," and should have the computation capability to process the selected optimisation technique.

In this research, the optimisation of the Ad hoc routing protocol has been designed to accommodate an intelligent unit for the whole network. If another factor is to be considered, such as the data rate, the decision issue will not be important as each individual network node can send its packets at a rate that the node is comfortable with. In this case, the intelligent unit could be embedded in each network node for an individual decision and each node could decide its optimum data rate.

To imagine this decision assumption in an Ad hoc realistic situation or any emergency situation, the Intelligent node represents the intelligent device in the control panel which advises a group of people via their devices, as shown in Figure 8.1. For example, a battle field (as in Figure 2.3) where the group leader's laptop represents the Intelligent node.

As known MANET devices have a limited battery life [1], by centralizing the optimisation process in one Intelligent node, other network nodes will be relieved from the data processing. This will also save the MANET nodes' power and time, as the other network nodes duty will be supporting the decision process by forwarding periodic Topology packets to the Intelligent node.

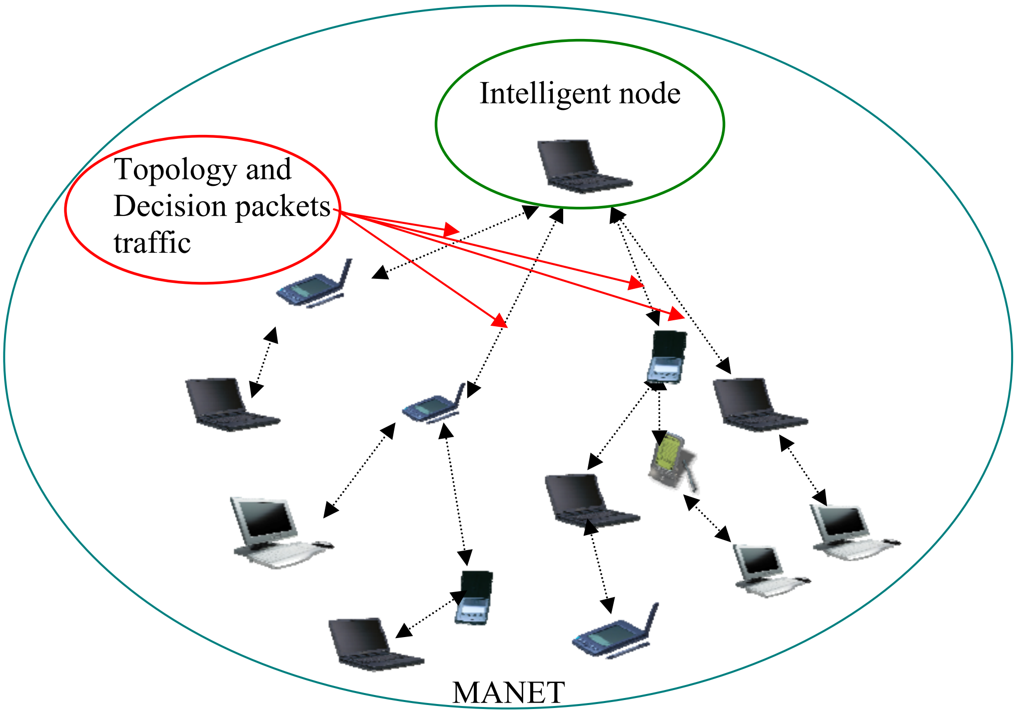

Figure 8.1: Intelligent node with other MANET nodes.

To develop the intelligent system so that the system can overcome the MANET power consumption problem [1], and to give the intelligent system a better chance of practical implementation in reality, MANET could be part of the Wireless Mesh Network (WMN) [2]-[3]; MANET could be one of the end-connected components of WMN wherein the intelligent system is centralized in the mesh router. MANET nodes could be the MWN client, as shown in Figure 8.2, in which MANET network is connected to the backbone of the WMN through a mesh router. In this case, one of the WMN routers (the red arrows) will have the responsibility of optimising the routing protocol for the whole MANET. In this case, more power and time will be saved for MANET as the MWN router will receive information and forward its decision from/to the MANET nodes. Figure 2.1 in Chapter 2 can also help to adapt this idea by embedding the intelligent unit in the fixed network router that will receive information and forwarding the decision from/to the mobile network.

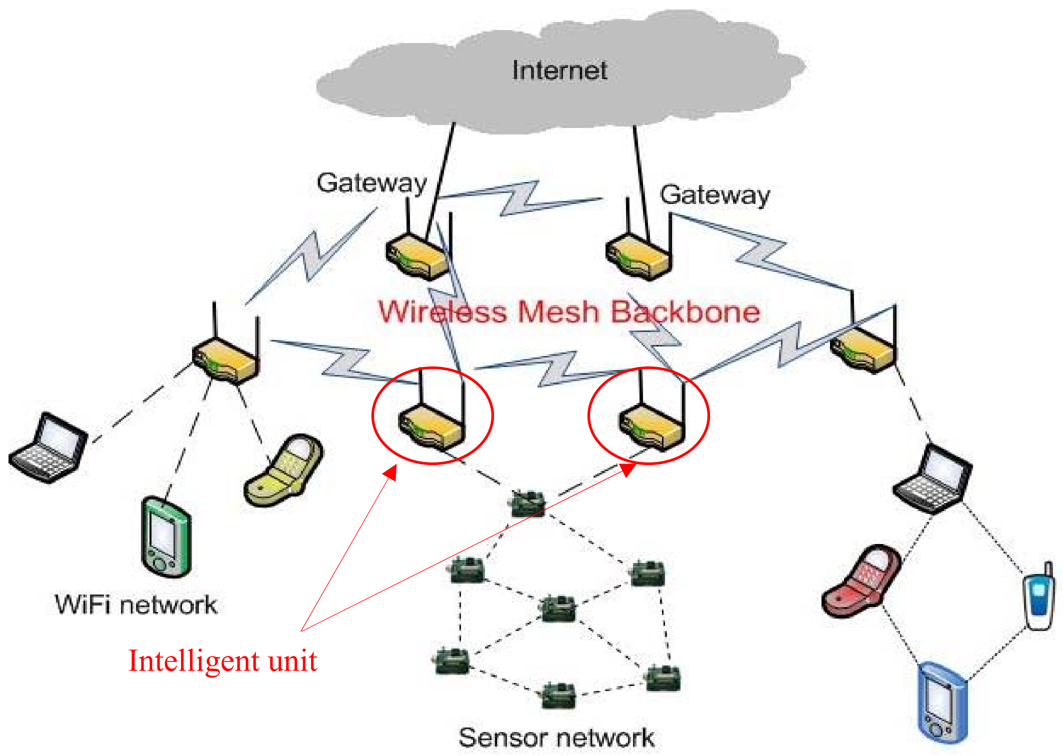

Figure 8.2: The Wireless Mesh Network (WMN) architecture [3].

8.2.2 Embedding the Intelligent Unit in MANET Nodes

The Intelligent node may, for reasons such as its battery being exhausted or left the network, cease serving the network and processing the intelligent optimisation. Therefore, this leads the network to suffer from possible single-point-of-failure if the network centralized the intelligent unit in only one Intelligent node. Consequently, the intelligent optimisation unit should be embedded in any mobile Ad hoc node that has the computation capability to accomplish the optimisation procedure. This will reduce the possibility of single-point-of-failure by having other nodes in the network embed this intelligent optimisation unit. As a result, if the Intelligent node fails, another nominated node will trigger its intelligent optimisation unit and become the new Intelligent node.

8.3 Implementation

This chapter implements the green arrows sequence presented in Chapter 4 (see Figure 4.1). The components discussed previously (Modeller and Optimiser) were assembled and joined with the switching technique (that will be explained in details in this Chapter) to create the I-MAN routing protocols optimisation system.

The system demands network topology information. Therefore, to solve this request problem, Topology packets are sent to the I-MAN routing protocols optimisation unit, as shown in Figure 8.1. Each Topology packet contains the node's mobility and the routing protocol in use.

The optimisation block diagram shown in Figure 8.3 illustrates the optimisation unit embedded in the Intelligent node, and represents the operations of the I-MAN optimisation unit in sequence. The unit consists of the Communication Gate, Information Stack, Optimiser, Modeller, and Decision Maker. As given below.

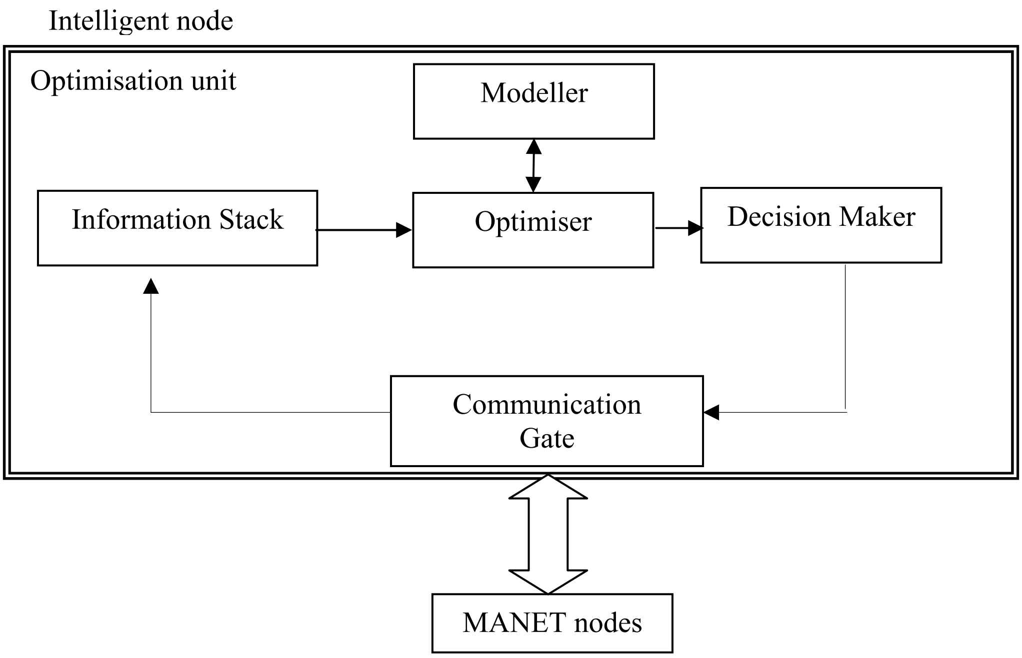

Figure 8.3: I-MAN optimisation unit blocks diagram.

First, the Intelligent node's Communication Gate will forward the Topology packets received from the network nodes to the Information Stack. Next, the Information Stack will deduce the current network context (the requested information parameters are: network size and average mobility). Afterward, the Information Stack will update the Optimiser with the new context (the roles of the Information Stack are explained in more detail further on; see the flowchart shown in Figure 8.4). The Optimiser then generates its solution for the current context with the support of the Modeller to predict the network performance metrics for each solution. The protocol's performance metrics help the Optimiser to not only evaluate the routing protocol in operation, but also determine the optimum routing protocol, as the optimum protocol for the network will be selected based on its performance. The selected routing protocol should have the best cost, which results from a combination of the desired parameters for less data drop, less delay, lower loads, less RA, and higher throughput. The decision will then be fed to the Decision Maker. The latter will conclude the switch time and reference it with the new optimum routing protocol in the Decision packet. Next, the Decision Maker will send the Decision packet to the Communication Gate. Finally, the Communication Gate will start feedback of the Decision packets to the network nodes.

Figure 8.4 shows a flowchart of the I-MAN routing protocols optimisation system which focuses on the system implementation through the time scale. First, the system parameter should be initialised; here, OPT is the parameter that represents the optimisation unit condition. If OPT = 0 that means this is the first run for the unit, and also means that the unit did not receive Topology packets before (the current context information) from the network. Whereas if OPT > 0, this means that the Optimiser was previously activated and chose the optimum routing protocol after receiving previous Topology packets.

After the network nodes send the Topology packets to the Intelligent node, the Information Stack will start its procedure, as shown by the flowchart sequence in Figure 8.4 and outlined below:

The first role is to count and gather each packet received from the Communication Gate to conclude the total network size, utilising the nodes counter.

The second role is to extract the node's mobility and the protocol name in operation from the node's Topology packet; then the node's mobility will be added with the others nodes mobility.

The third role is to buffer all the network topology information until time T_1,

as T_1 = current simulation time + Threshold_1, (8.1)

where Threshold_1 is the sent delay allowances, or the estimated time for all the network nodes' Topology packets to be received by the Intelligent node.

The fourth role is to calculate, at time T_1, the Optimiser requested parameters; network size (nodes counter); and Average Mobility. The total of nodes counted will be the network size, whereas the average nodes mobility will be calculated by adding up all the nodes' mobility and then dividing the result by the network size previously calculated.

The fifth role is to compare the Information Stack context results: the network size and the average mobility. If OPT = 0, then these results will be forwarded to the Optimiser directly but if OPT > 0, then the results should be compared to or matched with the network context from the previous period (that should be stored in the Information Stack). If the matching procedure result is negative, this means that the contexts are different and there will be new inputs to the PSO Optimiser. However, if the matching procedure result is positive and the context values are the same, then that means the network context did not change. In such case there is no need to activate the Optimiser as the same previous decision will be reached. Also, there will be no need to send Decision packets from the Intelligent node to the network nodes.

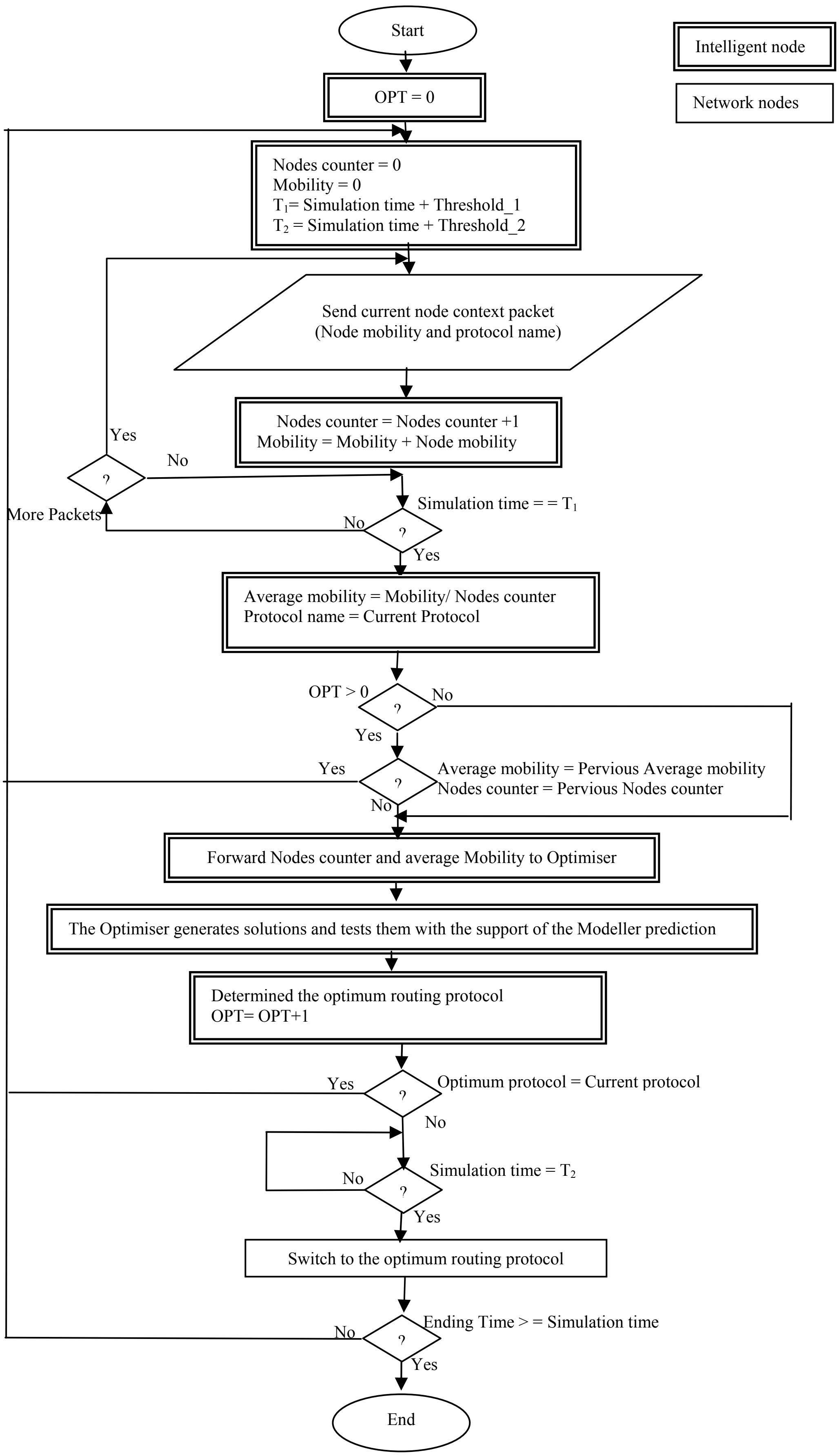

Figure 8.4: I-MAN routing protocols optimisation system implementation flowchart.

Figure 8.4 presents the Modeller role in predicting the network performance for each protocol and then sending it to the Optimiser to determine the optimum protocol. The flowchart also illustrates the Decision Maker’s role after the Optimiser concludes its decision (that is, sends the Decision packets). The packets contain the new optimum routing protocol name plus switching simulation time (T_2) to the Communication Gate,

as T_2 = current simulation time + Threshold_2, (8.2)

where Threshold_2 is the delivery delay allowances or the estimated time for the Decision packets sent from the Intelligent node to reach all the network nodes.

The Decision Maker will decide the exact simulation time T_2; as in, the time that the network nodes should adopted the new optimum protocol mechanism. The Communication Gate will then broadcast the packets to all the network nodes. If the optimum routing protocol is similar to the current routing protocol in operation, then the Decision Maker will not send Decision packets to the Communication Gate.

8.4 MANET Nodes Modification

To evaluate the intelligent system, the I-MAN routing protocols optimisation system was implemented with the support of the Opnet^{TM}14 modeller that uses C++ programming language.

Two major modifications should be implemented to the wireless network nodes models in the Opnet^{TM}14 modeller: the first is for the node that will embed the intelligent unit (that is, Intelligent node); the second is for the other network nodes that will embed the switching technique. The following sections will illustrate the modification. Mainly, the modification (the optimisation unit or the switching technique) was in the MANET node's IP process model. Figure 8.5 shows the *original* IP process model for MANET nodes in the Opnet^{TM}14 modeller.

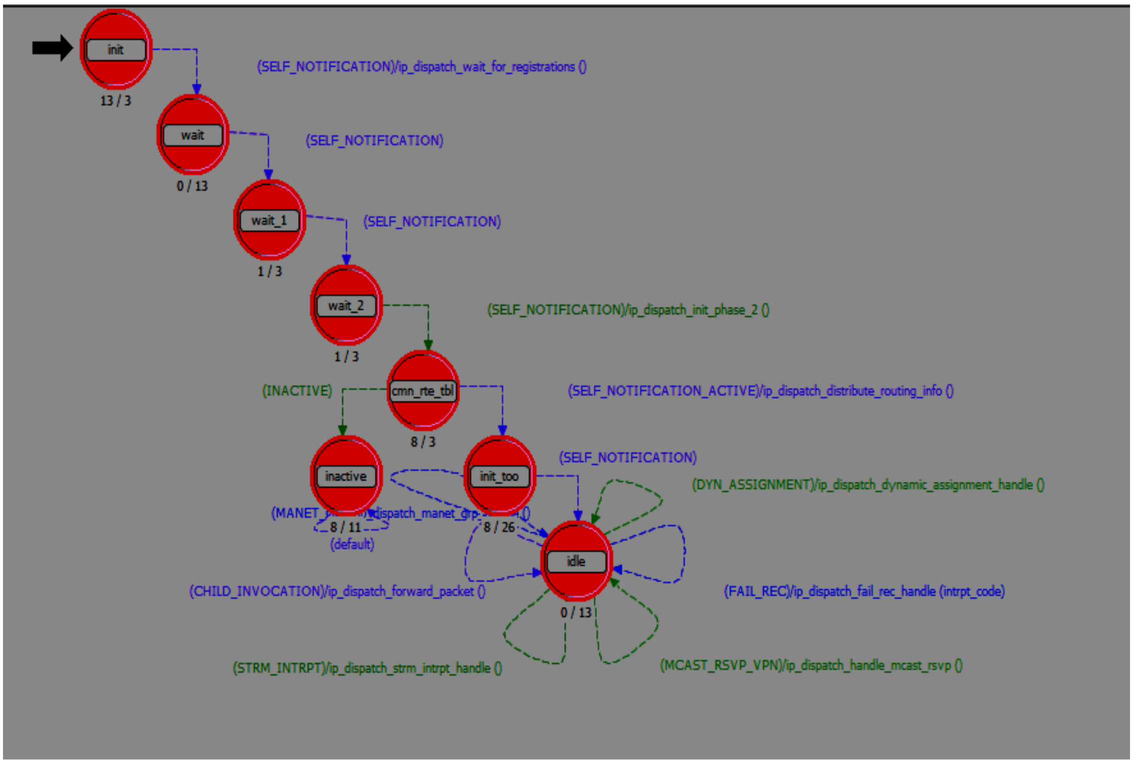

Figure 8.5: The original IP process model for MANET node in Opnet™14 modeller.

8.4.1 Creating the Intelligent Node

In Section 8.2 a conclusion was drawn that, in order to create the intelligent optimisation system, at least one of the Opnet™14 modeller MANET nodes should embed the intelligent optimisation unit in their process model. Therefore, the entire intelligent optimisation block diagram in Figure 8.3 should be included and embedded in the Intelligent node. As illustrated in Figure 8.6, the Information Stack component is divided between the init and idle processors (the thin black arrows). Therein, the green process model with the title NF-PSO contains two major components: the Optimiser and the Modeller (the double black arrow). Finally, the Decision Maker component is based in the idle processor (the thicker black arrow).

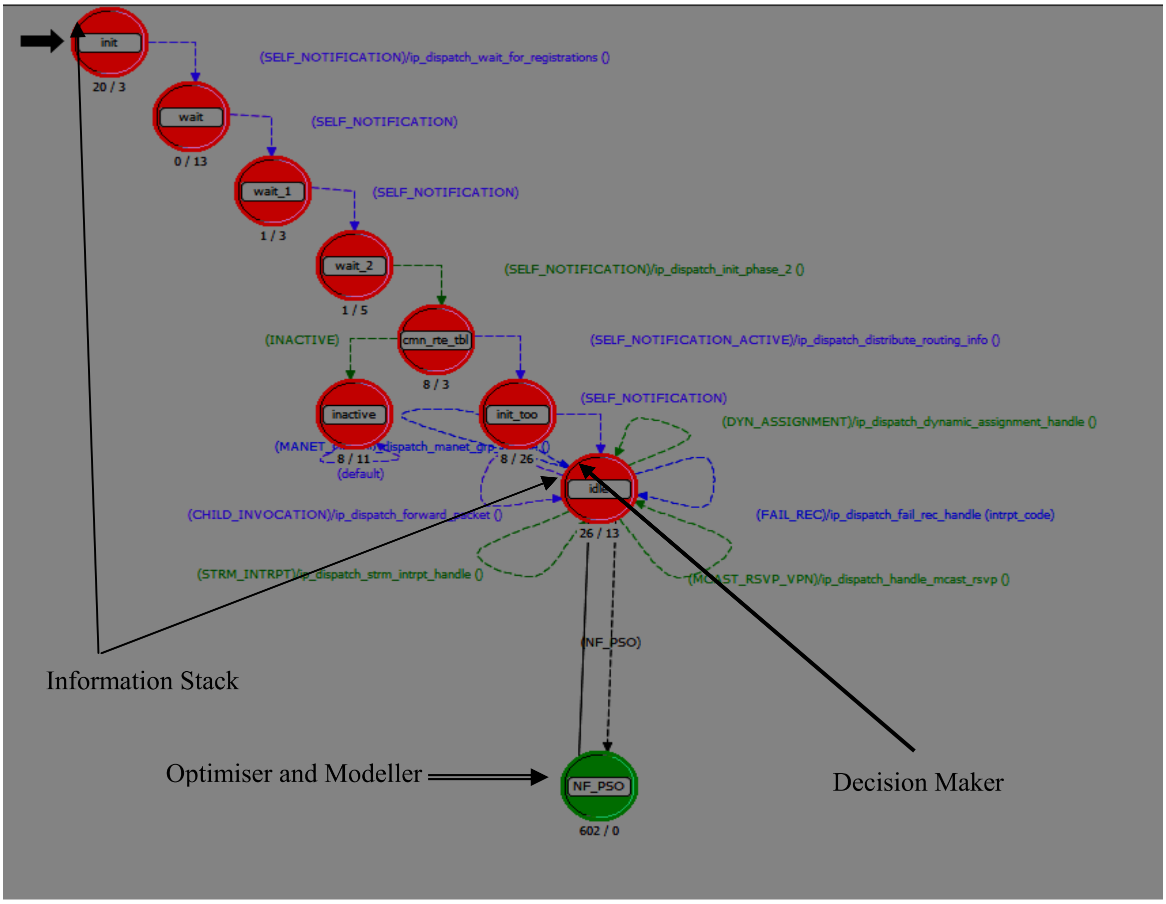

Figure 8.6: The IP process model for Intelligent MANET node in Opnet™14 modeller.

8.4.1.1 *Embedding the Information Stack*

The init process creates and initializes two counters: the Nodes and the Mobility counters. When a Topology packet is received from the MANET nodes, the init process will send an interruption command to the idle process. The Nodes counter will increase by one with every received packet. The packets collection process will continue until T_1. At time T_1, the value of the Nodes counter represents the total number of the network nodes in the MANET.

The Topology packet also contains the node's mobility. For every Topology packet that arrives, the node's mobility will be extracted and added to the Mobility counter; then the packet will be destroyed. The Mobility counter will keep summing the nodes' mobility until time T_1, when the average mobility is calculated by dividing the Mobility counter value by the Node counter.

8.4.1.2 *Embedding the NF Modeller*

After time T_1, and after calculating the MANET context parameters, the idle process will send an interruption command to operate NF-PSO process. Then the network performance will be predicted using the network performance models.

In the NF-PSO process model, the neuro-fuzzy (NF) Modeller created is based on the Sugeno modelling approach. Some of the details that are needed to program the Modeller, such as the type of the input membership functions, the number of rules for each performance model, and the constant parameters, are borrowed from the NF MANET performance models created in Chapter 6, wherein 15 models were developed.

Support from the Modeller ensures adoption of the optimum protocol by the Optimiser. Thus, to select the best protocol, the I-MAN Modeller generated the performance models (data drop, delay, load, retransmission attempt, and throughput) for MANET routing protocols depending on the network context

8.4.1.3 Embedding the PSO Optimiser

For each iteration loop, the Modeller will send the performance parameters values to the Optimiser that will start the optimisation process. To create the PSO Optimiser, the optimisation technique is embedded in an NF-PSO process model based on the practical swarm optimisation velocity Equation (7.1) and position Equation (7.2) [4].

PSO, the process that inspired from nature, was set with three dimensions swarm to represent the two inputs: network size and average mobility, and the one output the routing protocol. The size for the swarm was 10, iterated ten times, with an accepted error of less than 1×10^{-10}. The PSO Optimiser objective function is based on the cost function in Equation (7.4). In this case study, the value for w was 0.7298; the values for φ_1 and φ_2 were 1.49618, whereas r_1 and r_2 were calculated randomly. The best objective, the performance parameters least Mean Square (MS), will determine the optimum protocol, where the selected protocol has a combination of the parameters for the least normalized data drop, the least normalized load, the least normalized delay, the least normalized RA, and the highest normalized throughput. The Optimiser results will then be forwarded to the Decision Maker.

8.4.1.4 Embedding the Decision Maker

First, the Decision Maker compares the Optimiser results with the current routing protocol in operation. If the comparison results are the same, then there will be no action from the Decision Maker. However, if the comparison results are different, the Decision Maker will start to calculate T_2 and then create the Decision packet. The Decision Maker broadcasts these packets to all MANET nodes. The packet contains the routing protocol's name and switching time (T_2), or time at which all nodes should trigger the switching technique and adopt the suggested new protocol.

8.4.2 Creating the MANET Nodes

The original MANET node model should be modified to be able to perform the extra roles, as listed below:

a. ***Send periodic Topology packet***: each node in MANET creates a Topology packet containing its nodes' mobility and the protocol in use; the node then sends this packet to the Intelligent node at a predefined time.

b. ***Receive the Decision packet***: when a MANET node receives the Decision packet, it will extract the new routing protocol and the switching time from the packet (then the packet will be destroyed).

c. ***Adapt the switching protocol technique:*** the node will compare the switching time with the current simulation time. When the switching time is equivalent to the current simulation time, the node will use its switching technique to switch to the new routing protocol. As shown by the blue arrow in Figure 8.7, the (SW_Protocol) arrow leads the node to initialise the process of adapting the new routing protocol.

d. ***Buffering the data packets:*** packets are buffered until the new routing protocol is established.

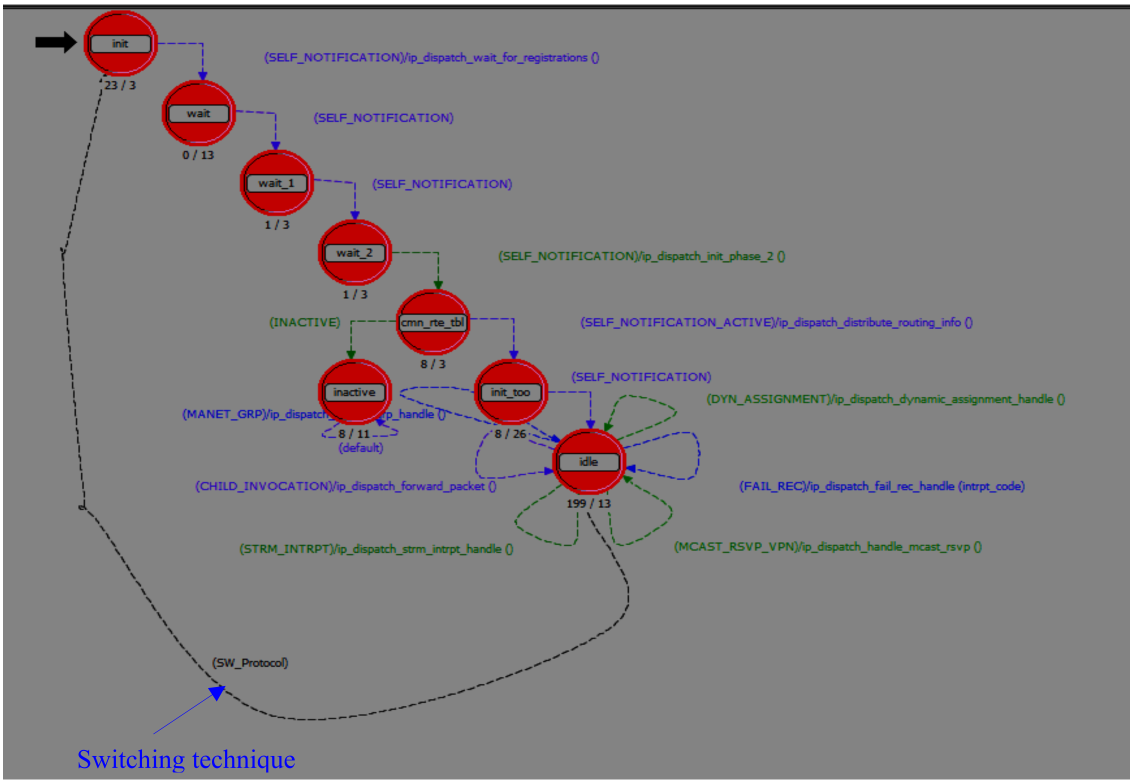

Figure 8.7: The IP process model for MANET node that adopts the switching technique in Opnet™14 modeller.

8.5 Case Study

To evaluate the proposed I-MAN routing protocols optimisation system, it should be implemented in a realistic scenario where the network context is changing. Also, the network operating the system should be compared to other networks' operating routing protocols in the same scenario conditions, without the system. Therefore, this case study presents one scenario example that addresses different contexts.

8.5.1 Simulation Environment

Four identical MANET simulation scenarios were executed. The same network scenario was implemented four times: first with the OLSR routing protocol, second with the DSR routing protocol, third with the AODV routing protocol and fourth with I-MAN. Each scenario ran for 4800 s. Nodes moving randomly distributed raw packets at 1 Mbps data rate to random destinations. Packets were generated with Poisson Inter-Arrival time. All scenarios were implemented with five context cases which lasted for nearly 16 minutes. Table 8.1 explains the context's duration, network size, and average mobility.

Table 8.1: The scenario's list of context.

Context Case	Time (minute)	Network size	Average mobility (m/s)
First	0 ~ 16	16	4
Second	16 ~ 32	55	4
Third	32 ~ 48	55	9
Fourth	48 ~ 64	21	9
Fifth	64 ~ 80	21	17

An image shown in Figure 8.8 for MANET ran context 1 for the fourth simulation, the I-MAN protocol scenario. The image illustrates the both working and the failed nodes, and also presents the position of each node at time 0.

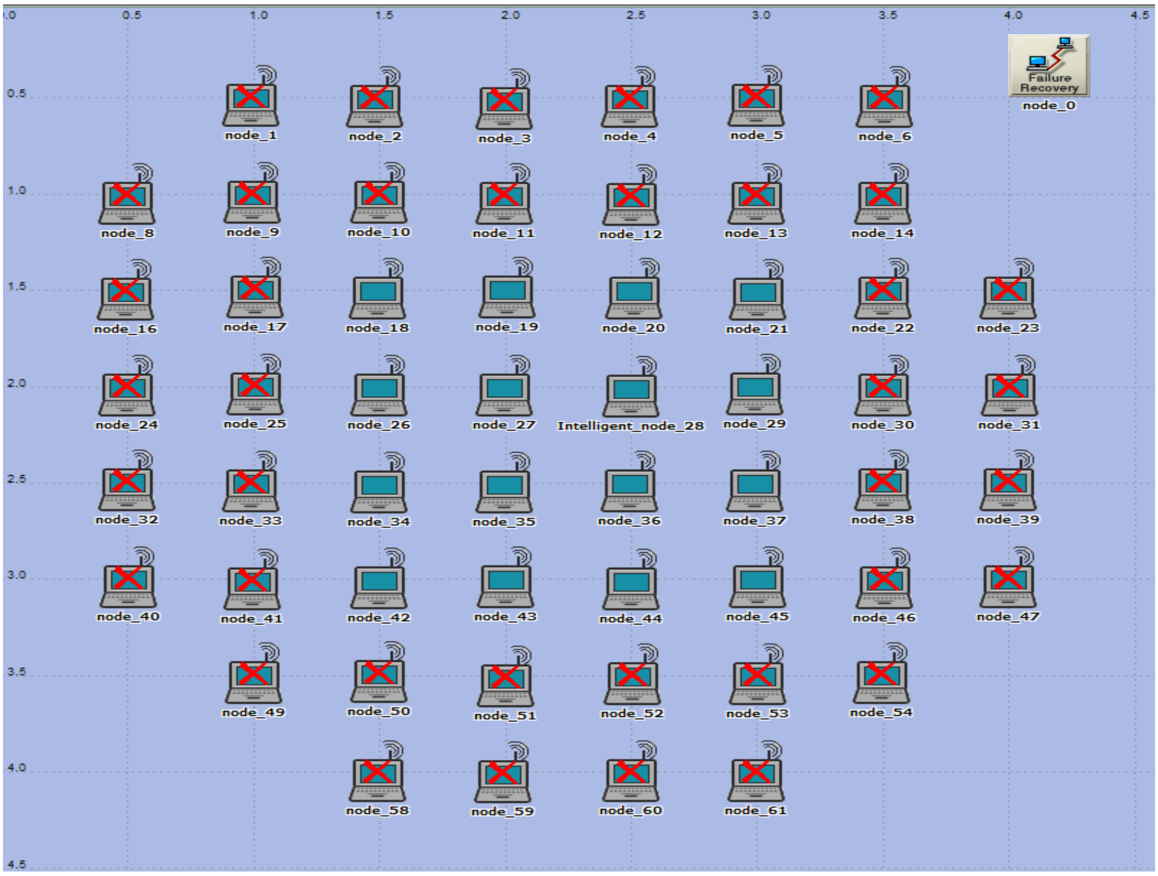

Figure 8.8: MANET image representing part of I-MAN scenarios: context 1.

Also, another image in Figure 8.9 for MANET ran Context 2 and Context 3 for the same scenario to represent the working and the failed nodes. As mentioned before, the nodes are moving arbitrarily so their position is always changing; therefore, this image does not present the nodes' positions in Context 2 and Context 3.

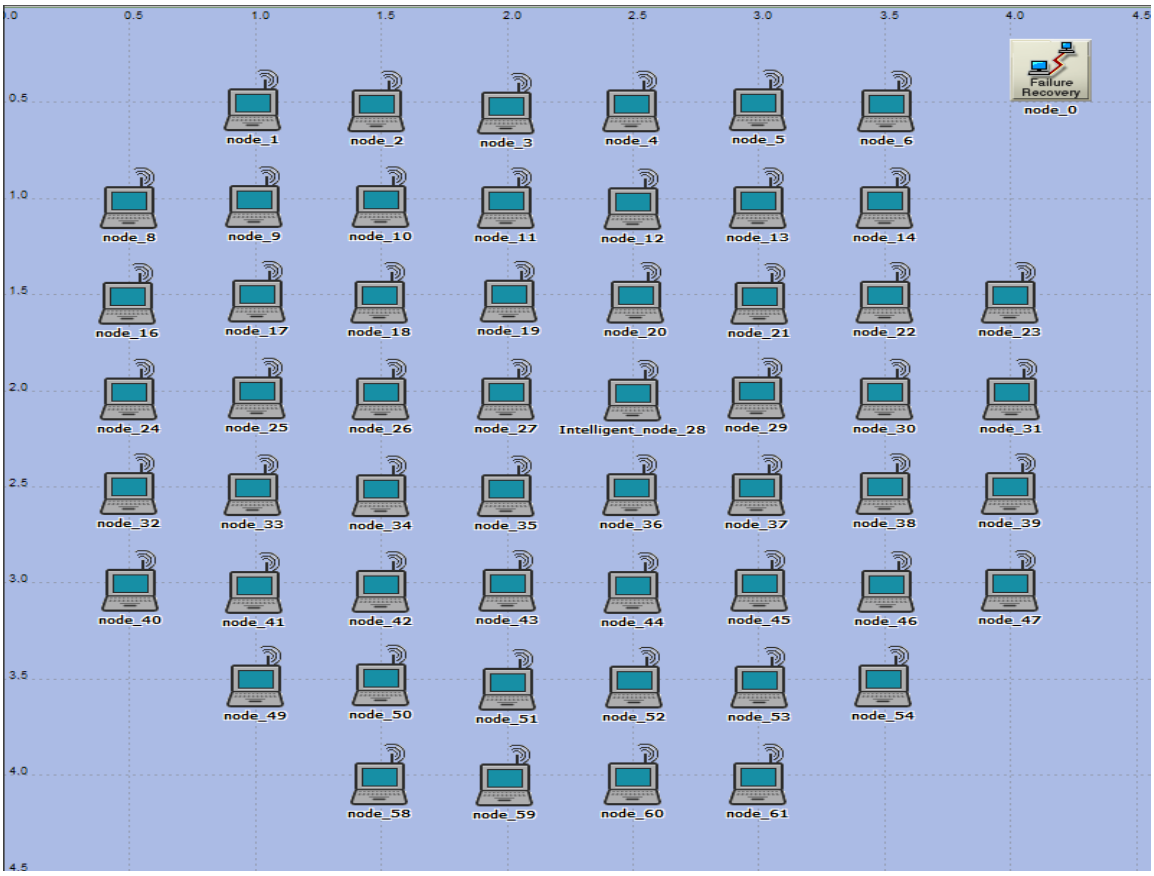

Figure 8.9: MANET image representing part of I-MAN scenario: Context 2 and Context 3.

The last MANET image in Figure 8.10 represents part of the I-MAN scenario with Context 4 and Context 5. This image presents the working nodes (network size) in this scenario, but not their positions in Context 4 and Context 5 (network mobility).

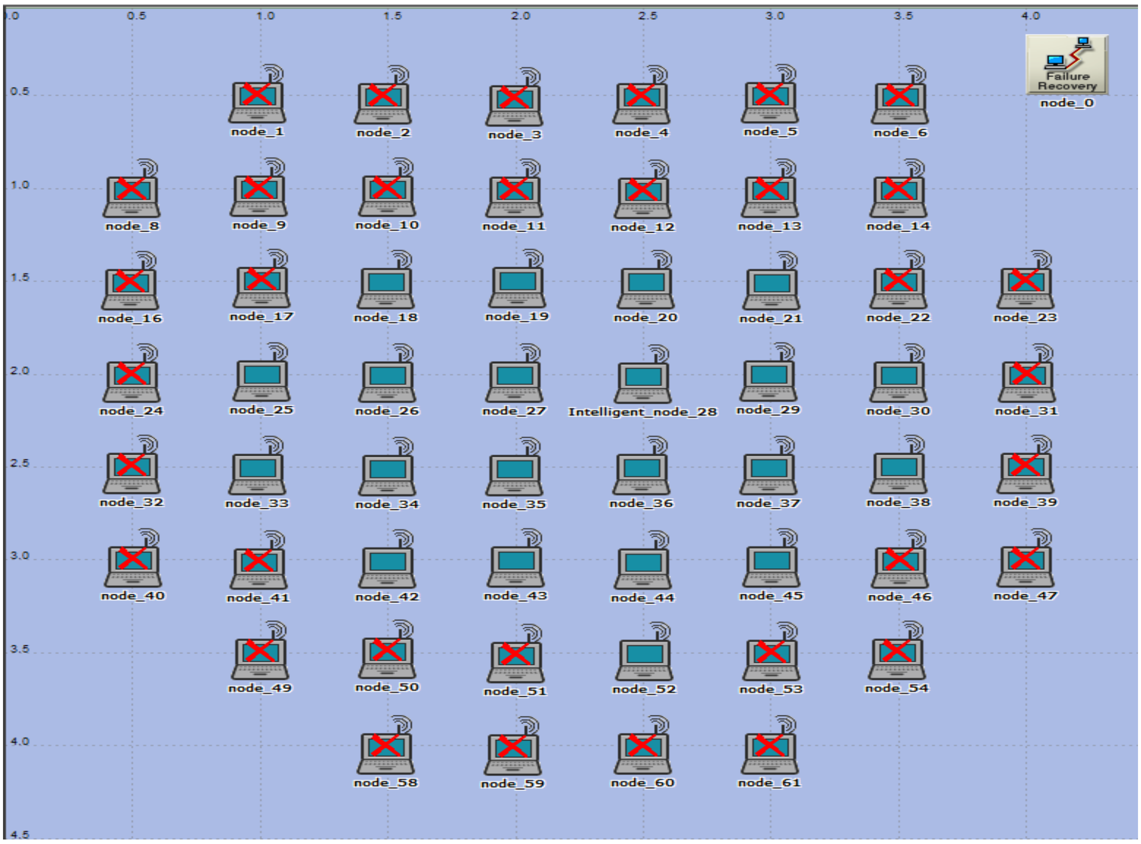

Figure 8.10: MANET image representing part of I-MAN scenarios: Context 4 and Context 5.

The simulation for the first three OLSR, DSR, and AODV routing protocols were ran with the same MANET properties used for the I-MAN scenarios: the same node position, the same failed nodes, and the same node trajectory, through the entire context. These will have the same I-MAN scenario images without the Intelligent node's responsibility. The image in Figure 8.11 is an example of MANET operating with one of the three protocols; this image represents part of the simulation for Context 2 and Context 3, as it presents the working nodes (network size) in this scenario, but not their real positions through the simulation.

Figure 8.12 clarifies the average mobility (bold font) for each context through the network simulation scenarios.

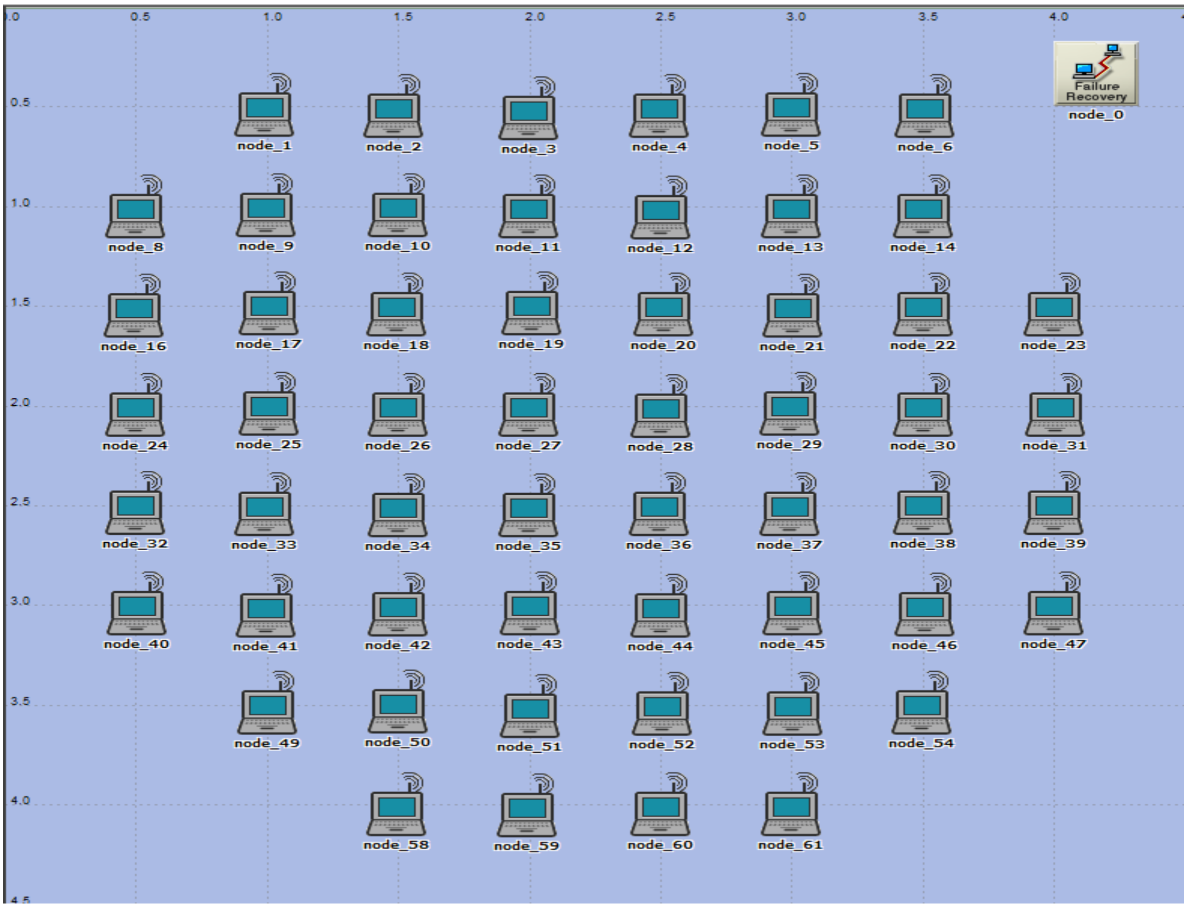

Figure 8.11: MANET image representing part of (OLSR or DSR or AODV) scenarios: context 2 and context 3.

8.5.2 Experiment Configuration

As mentioned before, the proposed approach is a scheme for routing adaptation. The I-MAN system's aim is to select a routing protocol for a specific MANET's context. Therefore, this proposal is actually a routing protocols optimisation system, but is not a new routing approach. As such, a few points should be considered before discussing the simulation results:

First, throughout the duration of the simulated scenario (I-MAN), the optimisation system might adopt more than one routing protocol. Therefore, for the sake of clarity, the protocol adopted by the I-MAN system will be called the I-MAN protocol but it is in fact one of the three routing protocols OLSR, DSR, or AODV. The term "I-MAN protocol" will also erase the confusion in the results analysis and evaluation sections.

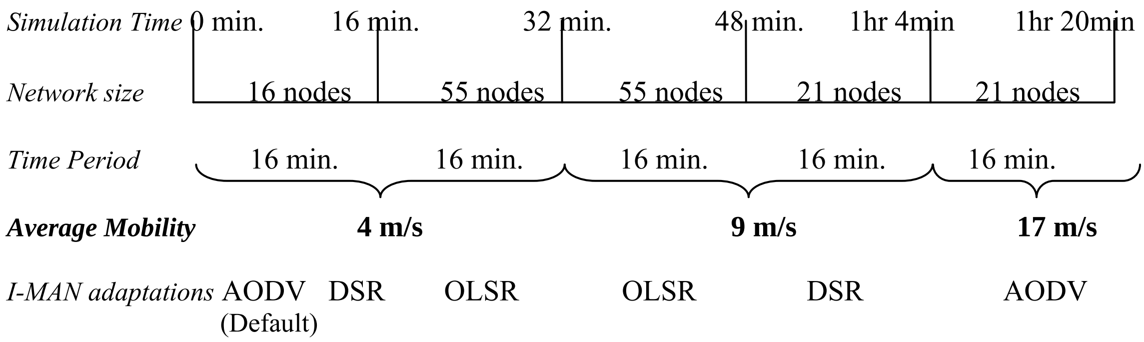

Figure 8.12: I-MAN routing protocol adaptations through the simulation period.

Second, in scenario four (I-MAN), the I-MAN protocol could be a combination of the protocols OLSR, DSR and/or AODV. Therefore, the I-MAN protocol will have the same characteristics of the adopted protocol. For example, if the I-MAN protocol adopts AODV routing protocol, it will have the same strengths and weaknesses of the AODV routing protocol mentioned previously in Chapter 4.

Third, in this case study, the first three MANET scenarios (OLSR, DSR, and AODV) were presented as a flat network, whereas in the fourth scenario for I-MAN, the MANET network was presented as a cluster network led by the Intelligent node.

Fourth, in the first three scenarios (OLSR, DSR, and AODV), MANET nodes have to send one type of packet: data packets; whereas in the I-MAN simulation scenario, the network nodes send two types of packets: data packets and Topology packets.

The types of packets needed for the simulations were defined as follows:

1. *Data packets:* These packets represent the data sent between the users. The packets' Inter-Arrival Time (T_{IA}) was 100 s, which means the data packets will be sent to random destination addresses every 100 s.

2. *Topology packets:* employed solely in the I-MAN scenario, each node had to send five Topology packets through the simulation time to the Intelligent node. The first Topology packet was sent at time 320 s, whereas the other four Topology packets will be sent from time 960 s until the end of the simulation, with 960 s Inter-Arrival Time.

Fifth, in the I-MAN scenario, there should be a sufficient time (Threshold_1) for the Topology packets to reach the Intelligent node and a sufficient time (Threshold_2) for the Decision packets to reach the MANET nodes. Therefore, deciding the amplitude for Threshold_1 and Threshold_2 effects the simulation dramatically. Thus, the value of Threshold_1 was chosen to be 0.5 s and the value for Threshold_2 was chosen to be 0.5 s.

Six, in the I-MAN scenario, the optimiser unit processes the normalization Equation (7.3) and the cost function in Equation (7.4) to determine the best protocol.

8.5.3 Simulation Results

Figure 8.12 illustrates the I-MAN system protocol adaptation through the simulation period against the network size and the average mobility. The figure shows the I-MAN system's reaction to each context change by adopting the ideal routing protocol (choosing the optimum routing mechanism) for that situation. The I-MAN protocol implements the switching procedure at T_2 to switch to different routing protocol from one period of time to another. The I-MAN scenario started with the default routing protocol AODV, then implemented the I-MAN system and adapting sequence of the protocols shown in the figure; the network first switched to the DSR routing protocol, followed by another switch to OLSR, then a switch back to DSR, and finally, a switch to AODV.

Through the I-MAN simulation scenario, The Optimiser has selected more than one routing protocol. Table 8.2 shows more details about the I-MAN protocol switching process during the scenario. The table includes the context case no., the previous routing protocol activated by the network nodes, the period for each context, the current setting, and the suggested optimum routing protocol (that is, the I-MAN protocol that should be in operation during the time period mentioned in the table). At the beginning of the simulation, the I-MAN protocol starts with the default routing protocol AODV (before triggering the optimisation unit) up to time 320 s. At that time, the nodes will start to send their current context Topology packets, represented by Context 1 (shown also in Figure 8.8). The I-MAN Optimiser will select the DSR routing protocol to be the I-MAN protocol for the period (320 s - 960 s). Therefore, all network nodes after time 320 s (320 + T_2) up to 960 s should adopt DSR routing protocol.

Table 8.2: I-MAN Optimal Selection for the Case Study Scenario.

Context Cases	Previous routing protocol	Time (sec)	Current settings		Optimal settings
			No. of nodes	Mobility (m/s)	I-MAN protocol acts as
default	----	0-320	16	4	AODV
1	AODV	320-960	16	4	DSR
2	DSR	960-1920	55	4	OLSR
3	OLSR	1920-2880	55	9	OLSR
4	OLSR	2880-3840	21	9	DSR
5	DSR	3840-4800	21	17	AODV

However, as shown in Figure 8.9, when the network size is increased to 55 nodes as in Context 2, OLSR is consequently chosen as the I-MAN protocol to route the packets and prevent the network performance from deterioration. In Context 3, when the nodes' speeds have increased to 9 m/s, the Optimiser selects OLSR as well. In this situation, since OLSR matches the previous protocol used during the previous simulation period, the Intelligent node's action was not to send Decision packets to the network nodes.

In Context 4, due to the dynamic nature of MANET, many nodes left the network; the network size thereby decreased to 21 nodes, as shown in Figure 8.10. As such, the I-MAN Optimiser selects DSR to operate the network instead of OLSR. However, when the mobility increased to 17 m/s in Context 5, AODV was the protocol selected to serve the network.

8.6 Comparison and Results Analysis

Visual comparisons between the four routing schemes (AODV, DSR, OLSR, and I-MAN) are presented in Figures 8.13 through 8.17. The comparisons were presented in terms of data drop, delay, load, RA, and throughput, respectively.

8.6.1 Data Drop

Figure 8.13 shows a comparison of the data drop variation for the four protocols throughout the simulation time. It can be seen that the I-MAN routing protocol has the lowest data drop followed by OLSR, then AODV, while the DSR has the largest data drop.

OLSR, a Table-Driven routing protocol that generates routing tables for the entirety of network destinations, was able to deliver most of the data without dropping it. Therefore, the OLSR data drop curve was better than the DSR and AODV data drop curves. The simulation data of OLSR (in Contexts 2 and 3) shows that OLSR was able to handle the scalable network efficiently.

On the other hand, the network scalability causes a noticeable data drop for the On Demand routing protocols DSR and AODV as a result of establishing routes in a large network.

As compared to the data dropped by DSR and AODV in Context 1, larger amounts of data were dropped by both in Contexts 2 and 3 (see Figure 8.13). Up to Context 3, DSR and AODV protocols had approximately the same attitude; in Context 4, however, the AODV routing protocol outperformed DSR as the AODV data drop was significantly less since the AODV protocol mechanism is adaptable to highly dynamic networks (see the comparison section in Chapter 4). Finally, in Context 5 the data drop for the two On Demand protocols was found to be acceptable. In general, AODV performance was better than DSR as the AODV's data drop was comparatively less than the DSR's.

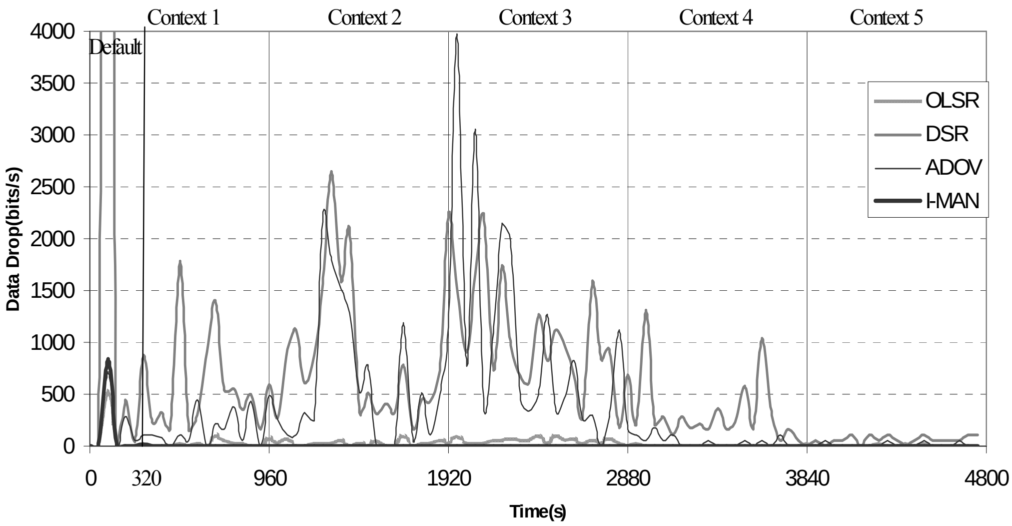

Figure 8.13: OLSR, DSR, AODV, and I-MAN data drop.

As is clearly shown in Figure 8.13, the best data delivery for the entire context is achieved by the I-MAN protocol, as it has the best data delivery rate. From time (0 ~ 320 s), the I-MAN optimisation unit was not yet active, therefore resulting in the drop of data. After activating the optimisation unit (from time 320 s up to the end of the simulation), this data drop was reduced significantly. The I-MAN system allows each network node a packets buffer to store the packets that could not reach their destinations. After establishing a new route, the packets will be sent again and, consequently, the data drop will be notably reduced.

8.6.2 Delay

Figure 8.14 shows the delay curves of the four protocols AODV, DSR, OLSR, and I-MAN throughout the simulation.

Comparing the three protocols' OLSR, DSR, and AODV delay curves in all the five contexts shows that the OLSR has the lowest delay curve, followed by AODV, and DSR, which had the highest curve.

The proactive routing protocol OLSR exhibited an excellent delay performance throughout the simulation's duration due to the periodic message and *MPR* mechanism that keeps the nodes' routing table updated and helps in delivering the packets without remarkable delay even when the number of nodes increases.

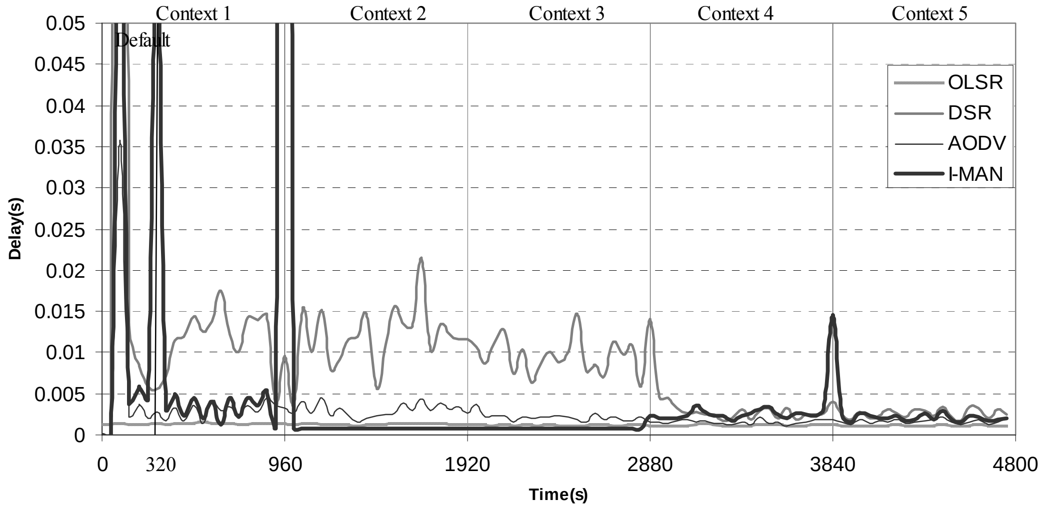

Figure 8.14: OLSR, DSR, AODV, and I-MAN delay.

Higher delay rates were obtained for the On Demand routing protocols AODV and DSR since whenever a source needs to send packets to a destination, the On Demand routing protocols apply the *Route discovery* mechanism if the destination address is not available in the source routing table.

Furthermore, network scalability has an effect on the DSR delay rate, as shown in Figure 8.14, throughout the simulation time and up to 2880 s. Given the changes in the Contexts 1, 2, and 3, the DSR delay rate increased as a result of increasing the network size. The delay rate increased because of the implementation of the DSR's routing cache mechanism (for more detail, refer to the DSR weaknesses described in the comparisons made by Section 4.4.5.2).

Figure 8.14 also indicates that the I-MAN protocol behaviour varied throughout the simulation time. From time 0 s up to time 320 s, the delay rate was high because the network was adopting the default routing protocol (AODV); as such, the intelligent unit was not activated during this period of time. After time 320 s, the I-MAN optimisation unit became operative and selected the DSR mechanism as the optimum routing protocol. Consequently, after applying the I-MAN switching mechanism and adopting the DSR protocol, the network delay rate was clearly reduced. From 960 s up to 2880 s as represented in Contexts 2 and 3, the I-MAN protocol adopted an OLSR mechanism, yielding an approximately constant delay rate. In contrast, the I-MAN protocol in Contexts 4 and 5 produced slightly higher delay rates with acceptable levels.

In Figure 8.14, there was a rapid increment in the delay rate occurring at time 320 s, 960 s, and 3840 s due to the Decision packets that are sent by the Intelligent node to the network nodes.

8.6.3 Load

Figure 8.15 shows the network load graphs operating the four protocols AODV, DSR, OLSR, and I-MAN through the simulation time.

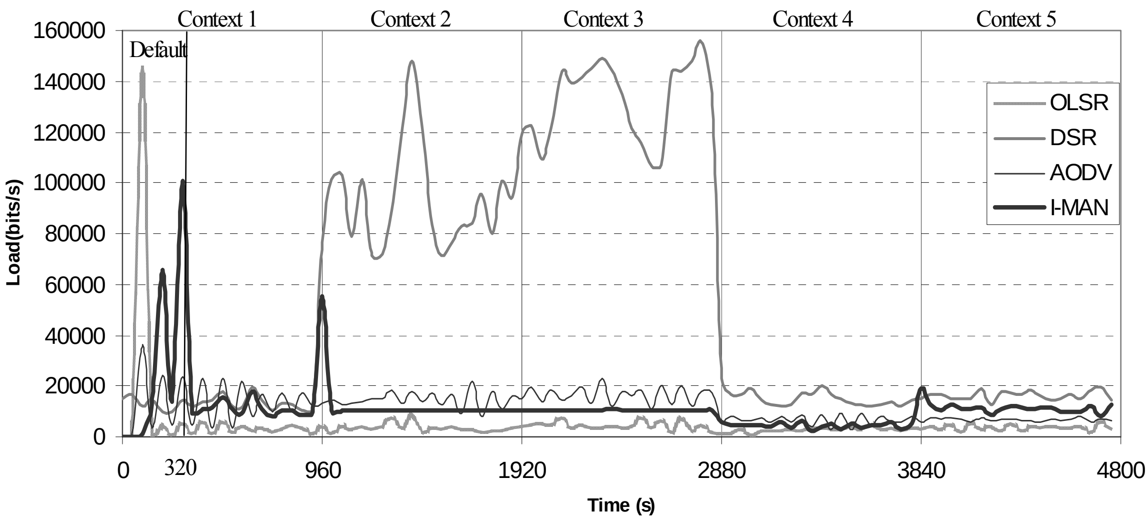

Figure 8.15: OLSR, DSR, AODV, and I-MAN load.

In comparing the load graphs for the three protocols OLSR, DSR, and AODV throughout all network context changes, it appears that the DSR routing protocol has the highest load, the AODV the second highest, whereas the least load was for OLSR routing protocol.

The updating of OLSR routing tables assists the protocol in obtaining the least load, whereas the AODV sequence number technique aids in the protocol load reduction. On the other hand, DSR load was the highest through the whole simulation, especially in Contexts 2 and 3, as the network scalability dramatically affected DSR operation and created load over the entire network. In Contexts 4 and 5, however, the load was reduced drastically as a result of the network size reduction. In these Contexts (4 and 5), the DSR multi-routing path strategy pays off, so that if the route established earlier is broken, then the source will search its route cache for another ready-route to that destination. If a ready-route is found, the source does not have to establish a new *Route discovery* and will send the packets through the second backup route. Therefore, the source will save both time and power.

In Figure 8.15, the I-MAN graph shows the changes in the load, as I-MAN load decreases and increases following the I-MAN adopted protocol. The graph clearly shows the I-MAN mechanism switching to different protocol at times 320 s, 960 s, 2880 s, and 3840 s. After 320 s, in Context 1 the load level was acceptable when the I-MAN Optimiser was activated. During the period from 960 s to

2880 s, as represented by Contexts 2 and 3, the I-MAN protocol switched to the OLSR mechanism and the I-MAN load graph was approximately stable. In Context 4, the I-MAN protocol reduced load by using the DSR mechanism whereby each node has their route cached; however, with Context 5, the load increased reasonably because in this instance the AODV mechanism was adopted.

8.6.4 Retransmission Attempts (RA)

Retransmission Attempts (RA) is a traditional mechanism for detecting the congestion in the network; therefore, RA is similar to packet loss. Figure 8.16 shows RA graphs for the four protocols AODV, DSR, OLSR, and I-MAN through the simulation time.

The figure shows that I-MAN accomplished the best results as it has the least packets retransmission attempts. The second best results were obtained by the OLSR protocol. The DSR protocol had more packets to retransmit, whereas the AODV protocol appeared to have too many packets to retransmit.

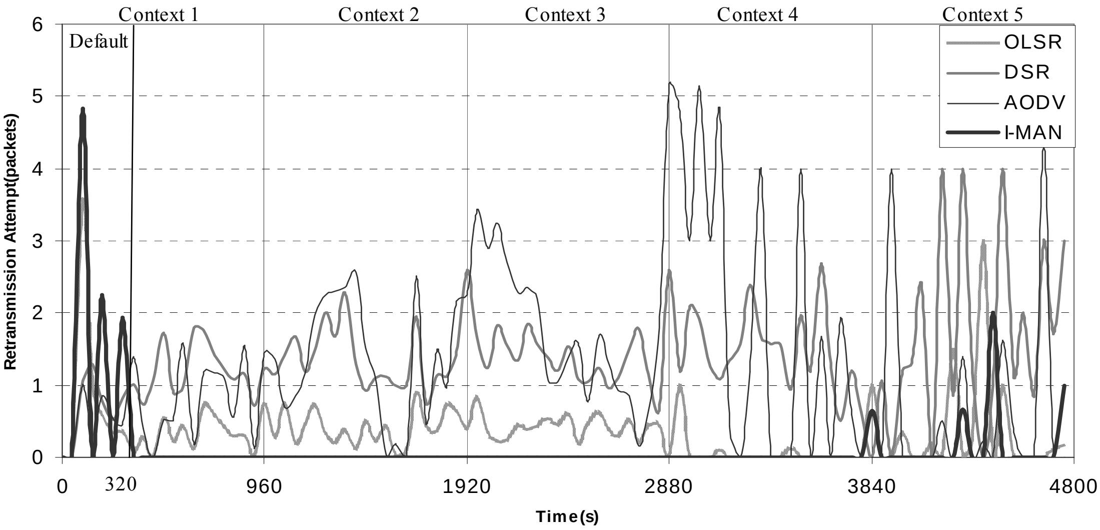

Figure 8.16: OLSR, DSR, AODV, and I-MAN Retransmission Attempts (RA).

The OLSR routing update table reduces the packets' RA as most of the packets reached their destination. Also, the DSR route cache assists in transmitting the packets through the storied backup-ready routes if the route used is broken; whereas AODV has no backup plan to reduce its RA. However, in Context 5, AODV was better than both OLSR and DSR as the number of AODV's RA packets was reduced significantly. This reduction is related to the AODV dynamic strategy that adapts to mobility. Also, the effect of high mobility on the DSR routing protocol, that is more RA packets are required, is clearly shown in the same period. As such, DSR was the protocol most affected in Context

5.

As shown in Figure 8.16, before operating the I-MAN unit, the default protocol AODV caused many packets RA up to time 320 s. After time 320 s, when the optimisation unit was activated, the packets RA was reduced significantly in contexts 1, 2, 3, and 4. This deterioration is related to the packets' buffer, secured in each node in I-MAN scenario, to hold the un-transmitted packets. However, in Context 5, the network's high mobility caused the dropping in data packets that need to re-transmit again, as shown in Figure 8.16.

8.6.5 Throughput

Figure 8.17 shows the throughput graphs for the four protocols AODV, DSR, OLSR, and I-MAN throughout the simulation time.

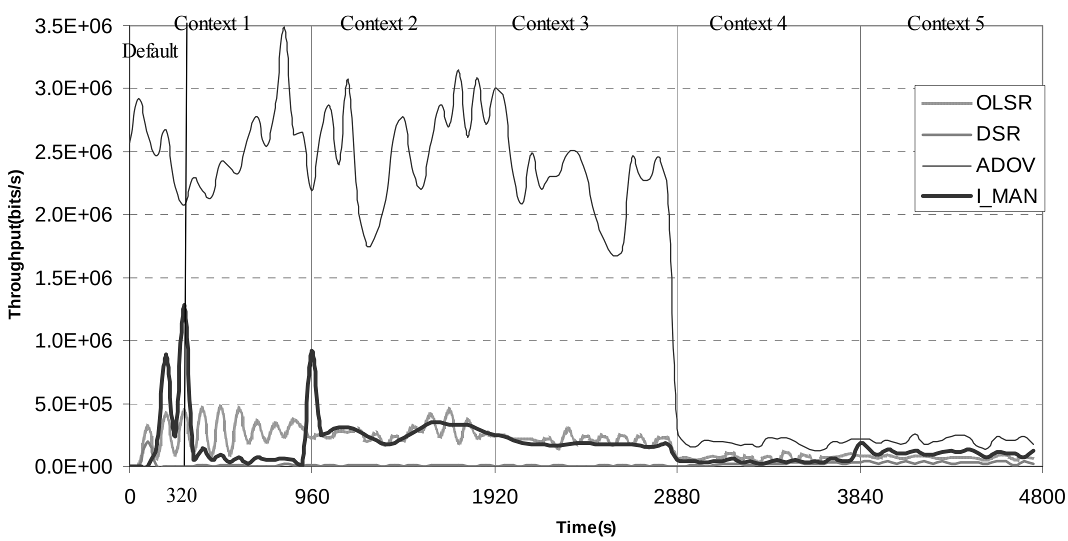

Figure 8.17: OLSR, DSR, AODV, and I-MAN throughput.

Comparing the three traditional protocols' OLSR, DSR, and AODV throughput, it appears that AODV yielded abundant throughput during the simulation, with OLSR second, and DSR yielding relatively low throughput.

The AODV protocol was thus able to forward more packets than the other two protocols; this characteristic confirms the protocol's adaptability to the network dynamic changes.

Part of the OLSR routing protocol throughput is the OLSR periodic update messages that increase the OLSR throughput.

Finally, DSR had fewer throughputs since it is not adaptable to the network dynamic changes and it does not use the periodic message technique.

As shown in the figure, I-MAN throughput results vary depending on the mechanism adopted through the simulation period.

As shown in Figure 8.17, there is an increase in I-MAN throughput at time 320 s, 960 s, 2880 s, and 3840 s due to the Decision packets forwarded by the network nodes. The reduction in the number of Decision packets between context 4 and context 5 kept the throughput graph flowing without a recognizable increase at that time, as the Intelligent nodes have to forward 21 Decision packets.

8.7 The Network Performance Cost Minimisation Function

The previous output performance figures—Figure 8.13 for data drop; Figure 8.14 for delay; Figure 8.15 for load; Figure 8.16 for Retransmission Attempts (RA); and Figure 8.17 for throughput—failed to clearly show the best routing protocol through the five context changes. For example, OLSR has the best results in terms of delay and load, whereas AODV has the best throughput. Therefore, a cost equation, as shown in Equation (8.3), has been suggested to evaluate the performance of the four protocols for the simulation's duration.

$$\text{Cost Minimisation} = \text{data drop} + \text{delay} + \text{load} + \text{RA} + (1\text{-throughput}) \tag{8.3}$$

To deliver and create the performance cost minimisation graph for each routing protocol, two steps are needed: first, normalizing the five output parameters: delay, load, throughput, data drop, and RA; depending on Equation (7.3) and second, applying them to Equation (8.3).

Figure 8.18 represents the cost minimisation graphs for the four routing protocols AODV, DSR, OLSR, and I-MAN. The protocol with the best performance cost minimisation graph is the one with the least cost minimisation function result.

In Context 1, the OLSR graph had a bad start with a cost minimisation of over 4, but started decreasing to fewer than 2.5 as the scenario progressed. In Contexts 2 and 3, the cost minimisation oscillated under the same level (2.5), whereas in Contexts 4 and 5, the cost minimisation was reduced to less than 1.

The DSR graph also had a sharp increase before 320 s, with cost minimisation value above 4.Then, after 320 s, the cost minimisation oscillated under 1 through Contexts 1, 2, 3, and 4; in context 5, however, the cost minimisation increases to above 1.

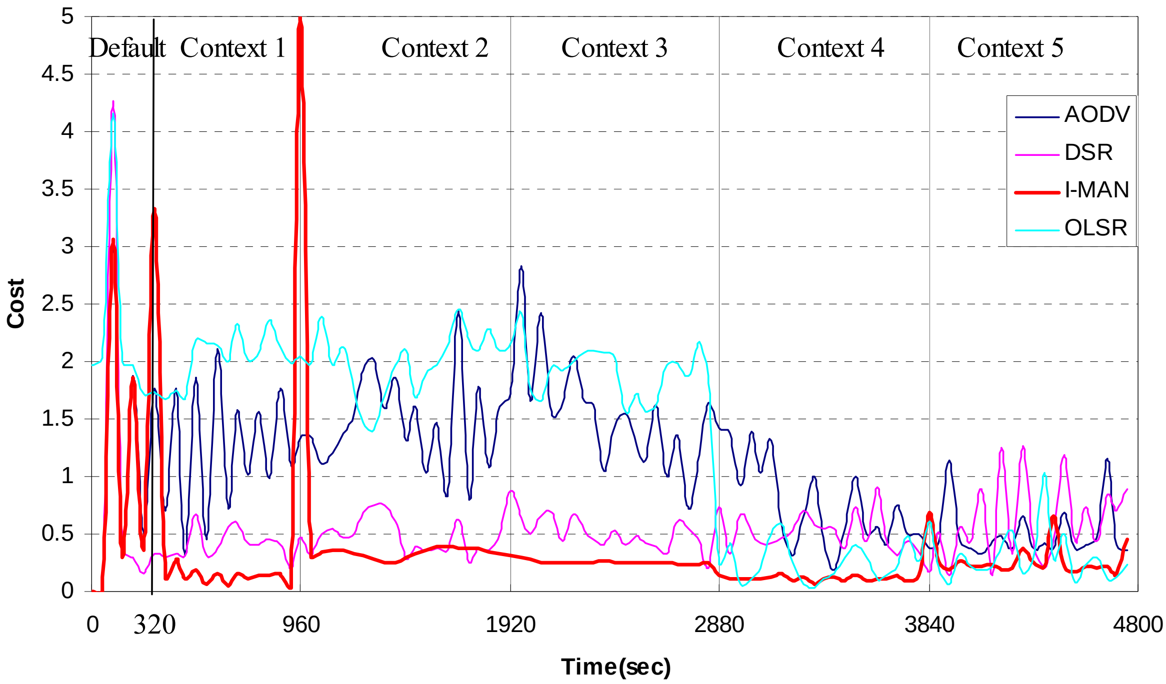

Figure 8.18: OLSR, DSR, AODV, and I-MAN cost minimisation function.

Clearly shown in Figure 8.18, the I-MAN protocol reported the least cost minimisation after time 320 s. Whereas from time 0 s up to 320 s, the I-MAN performance graph oscillated with high cost minimisation value (above 3) before operating I-MAN optimisation unit.

At time 960 s, the I-MAN performance graph suffers from high amplitude of cost minimisation due to the large number of Decision packets sent; however, the graph recovered after that time. Proceeding time 3840 s, the I-MAN graph rose above 0.5 twice because of the network's high mobility.

The saying "no pain, no gain" describes the intelligent system operating in MANET. Although, the Decision packets are essential to enhance the network performance for longer time but these packets also present an overload that affected the network for seconds.

In conclusion, from the time the I-MAN routing protocols optimisation system was first activated, the best visual cost minimisation graph was the I-MAN graph which also confirmed that the I-MAN protocol maintained the network performance as good as expected without incurring any degradation.

8.8 The Performance Cost Minimisation Function Quantitative Evaluation

This section evaluates the four protocols quantitatively based on the Integration formula below [5]:

$$\textit{Area under the curve} = \int_a^b f(x)dx \tag{8.4}$$

where f is the function of a real variable (x) for an interval [a, b] of real time. In this thesis, one of the most commonly used definitions of integration, the Riemann integrals mathematical method [6], has been considered to calculate the area under the curve (AUC).

Riemann's formula is presented below:

$$AUC = \sum_{i=1}^{n} \Delta_{f(t_i)} \Delta_i \tag{8.5}$$

The area under the curve was first divided into rectangular area samples, with each sample represented by its length (Δ_i) × its height ($\Delta_{f(t_i)}$). The area under each curve is then derived by summing all the samples areas.

In this case study, the performance cost minimisation for each protocol is equivalent to the area under the cost minimisation curve in Figure 8.18 for each protocol. The accumulated cost minimisation measurements for the four protocols were calculated and the results shown in Figure 8.19. The chart that has the minimum cost represents the best protocol. The figure shows clearly that the accumulated cost minimisation chart measurements for I-MAN are 37, which is less than the other three protocols' charts. The AODV cost minimisation chart came in second with 244 accumulated measurements, the OLSR cost minimisation chart came in third with 264 accumulated measurements, and the DSR cost minimisation chart was last with 339 accumulated measurements.

I-MAN cost minimisation chart results have confirmed quantitatively that the I-MAN protocol is the best protocol available.

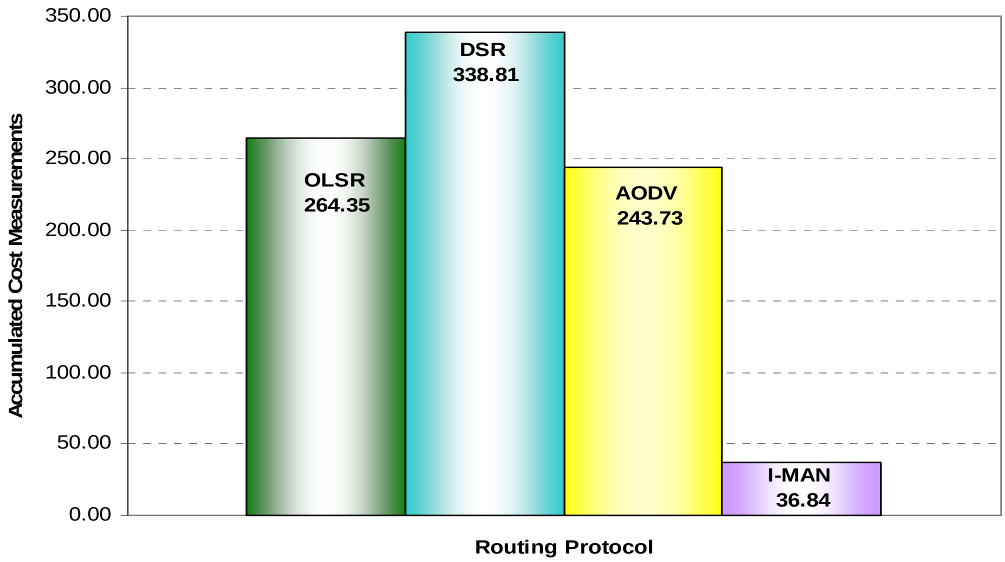

Figure 8.19: OLSR, DSR, AODV, and I-MAN accumulated cost minimisation measurements.

Figure 8.20 illustrates the cost minimisation in percentage chart for the four protocols. It shows that the best (minimum) cost was for I-MAN with 4.4%, whereas AODV came in second with 27.5%, OLSR came in third with 29.8%, and DSR was with 38.3 %.

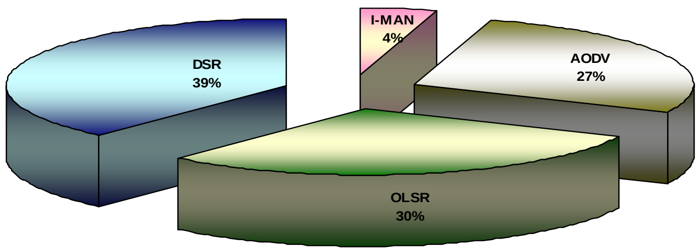

Figure 8.20: OLSR, DSR, AODV, and I-MAN cost minimisation percentage chart.

8.9 Studying the Inter-Arrival Time of Topology Packets

Since the I-MAN system depends on the Topology packets to receive the network context, the periodic Inter-Arrival Time (T_{IA}) for the Topology packets is therefore a critical element in implementing the I-MAN optimisation system.

If T_{IA} increases, there will be less Topology packets sent to update the Intelligent node with the new network context; thus, there will be less triggering and processing for the optimisation unit after T_1, and hence, there will be less Decision packets sent to the network nodes. This means there will be less load; however, increasing T_{IA} might affect the network performance, as the network context could change and the Topology packets be sent after a period of time to represent an old information.

In contrast, if T_{IA} decreases, there will be more Topology packets sent to the Intelligent node and, therefore, more processing work for the optimisation unit after T_1. Consequently, there will be more Decision packets, which means a higher load for the network. Moreover, in this case the Topology packets might contain the same network context that has yet to change. However, the I-MAN optimisation unit overcomes part of this problem by replying and sending Decision packets only when the contexts determined are not similar to the previously stored ones, as there will be no duplication of the Decision packets.

Therefore, to discover and study the effects of changing the period of the Inter-Arrival time T_{IA} for the MANET nodes' Topology packets, the I-MAN scenario in the previous case study was duplicated twice, resulting in three simulation scenarios that should run each time with different T_{IA}.: for the first scenario, T_{IA} set to 960 s (the original scenario); whereas for the second scenario. T_{IA} was decreased to 480 s which is half the value of the first scenario T_{IA}; and, in the third and last scenario, the Inter-Arrival T_{IA} was increased to 1920 s which is double the value of the first scenario T_{IA}.

The same procedure implemented in the original (first) scenario was also applied to the second and third scenarios, as each scenario's five output performance parameters were collected. The parameters are then normalized and entered into the same cost minimisation Equation (8.3) used by the original scenario. The cost minimisation results for the three scenarios are shown in Figure 8.21.

In Figure 8.21, I-MAN with T_{IA} = 480 s had high extra cost minimisation amplitude (approximately 5) at time 480 s; at time 4080 s, there is also another noticeable raise in the cost minimisation amplitude with a value of about 1.

The performance of I-MAN cost minimisation with T_{IA} = 960 s shows a similar attitude to the performance of I-MAN cost minimisation with T_{IA} = 480 s, with an extra increase in the cost minimisation between time 960 s and 1920 s.

The performance of I-MAN cost minimisation with T_{IA} = 1920 s shows an extra increase in the cost minimisation than the other two cost minimisation specially from time 480 s up to 1920 s, followed by an extra increase in the cost minimisation at time 3360 s to reach 0.5.

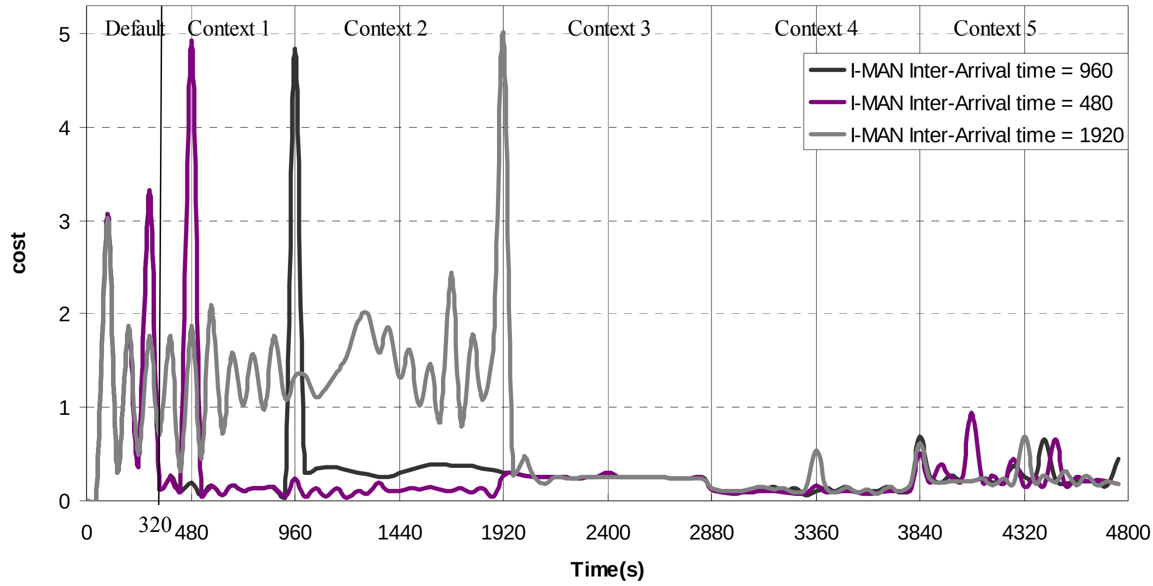

Figure 8.21: I-MAN optimisation system with three different Inter-Arrival time.

To evaluate the three costs in Figure 8.21 quantitatively, Equation (8.5) was used to conclude the total cost minimisation. Each cost minimisation result is presented in Figure 8.22. The figure shows that the minimum overall performance chart is I-MAN with T_{IA} = 480 s, whereas the overall performance chart for I-MAN with T_{IA} = 960 s came second, and the I-MAN chart with T_{IA} = 1920 s placed third, with the biggest accumulated cost minimisation measurements.

From these results, a conclusion was drawn that if the T_{IA} is decreased, it will enhance the network performance because it will keep the intelligent unit updated with the network context; in contrast, if the T_{IA} is increased it will feed the intelligent unit with old information which will lead to degradation in the performance.

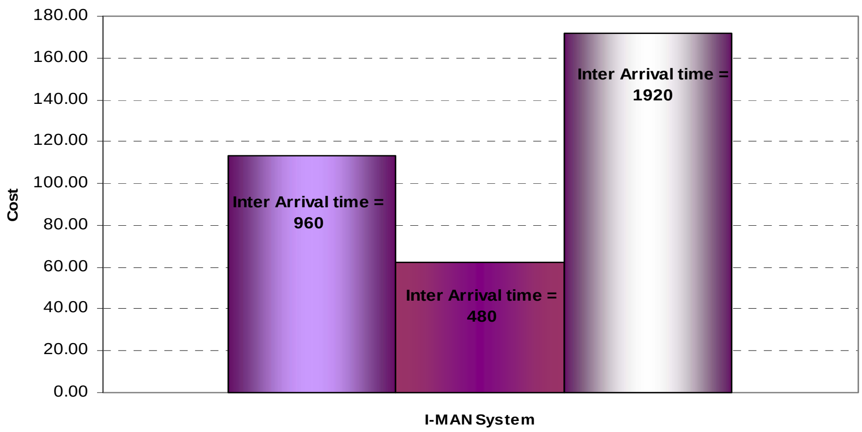

Figure 8.22: I-MAN optimisation system cost minimisation areas for three different Inter-Arrival time.

Also, another conclusion was drawn through studying the three scenarios; that is, T_{IA} should not be a constant time interval, as it should follow the network's needs. Thus, T_{IA} should increase and decrease according to the network context. For example, if the network average mobility increases, the T_{IA} should decrease and visa versa.

8.10 Case Study Limitations

The I-MAN optimisation system creates a self-organised system, as related by Dressler's [7] definition that state *self-organization is a process in which structure and functionality (pattern) at the global level of a system emerge solely from numerous interactions among the lower-level components of a system without any external or centralized control. The systems components interact in a local context either by means of direct communication or environmental observations without reference to the global pattern* (p.3020). The I-MAN optimisation system maintains a global state, derives operational behaviour from that state, and then distributes the globally valid state information among a number of nodes. Although, there are some limitations in the design of the I-MAN routing protocols optimisation system. Below is a list with the assumptions and synchronizations that should be made to ensure that the system will run successfully; the first point relates to the dynamic characteristic of MANET, whereas the other points relate to the I-MAN optimisation system design and implementation.

1. **Combinatorial stability**: In MANET, the topology always changes for many reasons, such as the nodes moving away from one network to join another or the nodes declining further participation in the transferring of packets. Also, any node could stop its participation to save its battery (lifetime), or because it's already failed and has an exhausted battery.

Throughout the case study scenarios considered in this thesis, the network topology changes many times; the scenarios included important context cases where the network decreased or increased in size, combined with an increase or decrease in mobility. To allow any routing protocol to function properly, a crucial assumption must also be stated here; that is, the rate of the topology change must not be greater than the rate of the state information propagation—otherwise the routing information will always be outdated and routing will be inefficient, or could even fail completely. A network that satisfies this condition is said to be combinatorially stable [8]. Therefore, in this case study, and specifically in the I-MAN simulation scenario (as this scenario sends Topology packets), this fact was taken into the account such that the context represented by network size and average mobility changes smoothly from one situation to another in a fixed period, for a duration of 16 minutes whereas the network Topology packets will be sent for the first time at 320 s and then for every T_{IA} equal to 960 s.

1. **MANET nodes embedding the system's protocols**: The I-MAN routing protocols optimisation system demands that all network nodes, the ones joining in or the ones leaving or the ones moving

around, should embed at least the routing protocols that the system has modelled and may implement. If not, the network nodes will be separated when the Intelligent node sends an order to the nodes to operate on a routing protocol they do not have.

In the I-MAN simulation scenario, I-MAN optimisation system requires that all MANET network nodes have the three protocols OLSR, DSR, and AODV embedded in them, and that the nodes also have the capability to operate the three routing protocols.

2. **Context-aware automatic computing system**: The I-MAN routing protocols optimisation system is a context-aware automatic computing system; therefore, it should be provided with context-rich information to undertake the intelligent decision-making, which in turn will provide timely information to the user.

   In the I-MAN case study scenario, the intelligent optimisation system demands topology information about the network. The system will be operated when it receives the network nodes' periodic Topology packets, and will then send the periodic Decision packets to the network nodes provided.

3. **The Intelligent node is known**: Related to the previous point, the intelligent system needs to collect/send information from/to devices; hence, the device embedded the intelligent unit should be a node well-known to the entire network nodes.

   In this case study, the I-MAN simulation scenario assumes that the Intelligent node was known by all other network nodes, so the network nodes will address the destination ID for their Topology packets with the Intelligent node ID address.

4. **No failure for the Intelligent node**: The I-MAN simulation scenario assumed that the Intelligent node:

   A. Could move all around the network area,

   B. Should not leave the network, and

   C. Had sufficient battery life to finish the simulation without any failure.

5. **Limited prediction**: In the I-MAN simulation scenario, the intelligent optimisation unit can predict the network performance for a range of network sizes, varying between 4 nodes and 64 nodes, and a range of average nodes' mobility, varying between 0 (m/s) and 20 (m/s). As such, the intelligent optimisation unit cannot predict any results for networks larger or faster than the aforementioned parameters given.

6. **No hidden nodes**: another assumption should be mentioned here, that there were no hidden nodes in this case study and that all network nodes were receiving all the packets that had been sent to them.

8.11 Summary

In this chapter, important issues have been raised that should be determined before implementing and simulating the I-MAN optimisation system with the Opnet^{TM}14 modeller software package. As in the chapter, it has been confirmed creating the Intelligent node for the system's intelligent unit to decide the optimum routing protocol and also embed the intelligent optimisation unit in all the capable nodes.

Also in this chapter, the Opnet^{TM}14 modeller nodes were developed to formalize the I-MAN optimisation system, as the network nodes must be modified for applying the Intelligent node decision in the simulation environment. The Intelligent node was also created, it must pass through three phases (shown in Figure 8.4 of the flowchart):

First, it acts as a sensor; the Nodes counter will be incremental whenever a Topology packet is received from the network nodes.

Second, it acts as an actuator, as the Optimiser will be actuated at T_1; and

Third, it acts as a predictor, predicting the network performance employing several protocols, the optimum routing protocol for that context, and the network nodes switching time, T_2.

In the case study, the I-MAN optimisation system was tested with the three protocols OLSR, DSR, and AODV. The I-MAN protocol has adopted a different routing mechanism from time to time in an attempt to maintain the network performance at an acceptable level. The I-MAN Optimiser (as shown in Table 8.2) tends to choose AODV for fast networks and OLSR for dense networks with low and medium mobility; DSR was selected for relatively small networks with low mobility. The results show that OLSR has the best results in terms of delay and load, whereas AODV has the best throughput. Therefore, a cost minimisation index that aggregates performance results from multiple response metrics into a single scalar value which quantifies overall system performance can lead to more in-depth cost minimisation evaluations and comparisons. In this chapter, the effectiveness of the proposed system has been confirmed by its clear cost-efficiency. As shown in the results, the I-MAN graph has the lowest cost in comparison to the other three traditional routing protocols.

In this chapter, accumulated cost minimisation measurements (area under the curve) was defined and used as a measurement or comparison tool to evaluate the performance of the I-MAN optimisation system and the three protocols.

This chapter also investigated the effects of deciding the period of the Inter-Arrival time, T_{IA}. The better network results were gained from the smallest T_{IA} period. In spite of these good results, the author believes that the best and optimum T_{IA} is the one that follows the network needs; therefore, T_{IA} should be variable with time, based on the network context.

8.12 References

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Chapter 9

Conclusions and Future Work

9.1 Summary

Over the past few years, there has been a growing interest in a pervasive, connected world, where distances shrink and virtual presence is everywhere. Next generation wireless networks, heterogeneous access technologies, Ad hoc and sensor networks, and new Internet technologies have become a part of this new world. The need for innovative, increasingly robust, self-organising, and context-aware networking protocols and techniques will challenge our current designs.

The previous sentences were taken from the call for the 8th International Conference on Telecommunications 2011 [1]. This call is one of many calls to find a routing protocol that will fulfil the network requirements, as investigations in this subject are ongoing and the present search has yet to achieve satisfactory results.

Therefore, the point of this thesis is that, although there have been many MANET routing protocols invented, each protocol is designed based on a particular context condition. This is problematic because network conditions are not constant and, in a MANET dynamic environment, that particular context condition will not last long. This problem could be solved in two ways: either inventing another routing protocol that considers all the context-aware parameters (as in the ICT 2011 conference call), or inventing a system that, given a change in the network context, selects the optimum routing protocol from a predefined list which contains all important and well-implemented routing protocols.

The research in this thesis started by surveying the area of mobile networks in general, and MANET in particular, to understand the communications field. Another survey was then performed to understand the role of optimisation in a MANET routing protocol. Next, this thesis presents a novel design for an optimised system which learns from the network's performance and predicts the optimal routing protocol for the network, called the I-MAN routing protocols optimisation system. This intelligent system will have the ability to adapt to variations in the network environment as the intelligent module selects the appropriate routing protocol according to the network's context.

Furthermore, the empirical RE technique and four other Artificial Intelligence techniques (ANN, NF, GA, and PSO) were defined and their functionalities explained in detail. Finally, the I-MAN routing protocols optimisation system was implemented in MANET after some modifications to the network nodes. Previously, the performance models data drop, delay, load, RA, and throughput, were trained related to the network parameters network size and average mobility, against each tested routing protocol OLSR, DSR, and AODV. Whenever the nodes start sending their context parameters, the system will start collecting data that represents the network behaviour against this new context. Then, the intelligent optimisation system evaluated and compared the effect of this new context on the network performance for each tested routing protocol to select the most suitable protocol for the current network context.

This system was evaluated and compared to traditional routing protocols (OLSR, DSR, and AODV). The calculation revealed that the minimum cost for I-MAN with accumulated measurements was equal to 37, whereas the AODV cost minimisation was 244 accumulated measurements, OLSR was 264, and DSR was 339. These results prove the efficiency of the proposed system.

9.2 Conclusions

The overall aim of this thesis is to design and implement a novel intelligent optimisation system to solve the context-awareness problem in MANET routing. The survey results in MANET routing protocols area applied a different taxonomy to MANET routing protocols and listed various classifications. Each classification (taxonomy) was based on one of the network characteristics. Therefore, the network characteristics play an important role and are given priority in the design of a MANET routing protocol. This thesis also presents a new taxonomy added by the author, based on the routing metric. Also in this thesis, optimised MANET routing protocols were presented, with the protocols optimised either based on their routing metrics or based on deploying the optimisation techniques. The difference between this thesis proposal and other researches is that most of the other researches embedded their optimizing technique in the routing protocol, whereas this thesis proposes an optimizing system that is embedded in a network node. Thus, the literature review task has been fulfilled by presenting both an overview of the various taxonomies and previous optimisation work in the MANET routing protocol.

Moreover, the thesis aimed to find the best modelling and optimizing techniques compatible with MANET. The research was based on three modelling techniques (RE, ANN, and NF), and two optimisation techniques (GA and PSO). These techniques were then evaluated to determine one representative and accurate modelling technique, that is NF, and one optimisation technique that will be adopted, that is PSO, by the final MANET optimisation system implementation.

Finally, the proposed system was implemented in one of MANET node, the intelligent node, where the optimisation system was acting as a sensor to the network node and their mobility, then as an actuator that trigger the optimiser at a certain time, then as an evaluator by exam each routing protocol performance at that current context, and finally as a predictor to decide the optimum protocol. The I-MAN system proved to have the best cost minimisation compared to other MANET routing protocols. I-MAN has the best minimum cost with 4.4 %, whereas AODV came second with 27.5 %, OLSR came third with 29.8 %, and DSR was last with 38.3 %.

In this thesis, the I-MAN routing protocols optimisation system has considered the network nodes performance as one unit, so the performance of the network's individual nodes was not considered. Therefore, the output performance collected by the Simulator was for the entire network and not for each individual node in the network. The system observes network performance overall and depends on the performance cost for the decision. The optimisation unit (including the Modeller and the Optimiser) in the system could be used by each individual to optimise node characteristics such as data rate or power consumption.

The main drawback of the proposed scheme is the energy consumption and overload due to the collecting and sending of information Topology/Decision packets by/from the Intelligent node. Also, the system complexity will increase along with the network size. If the network size is large, delivering Topology packets to the Intelligent node and sending Decision packets from the Intelligent node will consume more time and energy, as the route to the Intelligent node will be longer than that of a smaller network. The load will also be increased due to the number of information packets that have been sent. Moreover, the system is required to have at least one node with a computation capability to assume the responsibility of the Intelligent node. The system incurs a few hundred milliseconds of delay due to the collecting and sending of information packets. The network nodes also incur some milliseconds of delay to establish the new route with the optimum routing protocol. Finally, the I-MAN optimisation system requires a preparation stage before operation time. In the preparation stage, all performance parameters are modelled in NF, with the equivalent modeller programmed in C++ embedded in the Intelligent node.

9.3 Achievements

The main achievement of the work presented in this thesis is the creation of a self-optimised MANET with the support of an intelligent heuristic optimised system. The optimisation role was handled by the network cluster head node, represented in this thesis as the Intelligent node. The second achievement is the application of an AI technique to model MANET performance; this achievement opens another research area in comparing and developing the MANET evaluation mechanism. Finally, the work presented in this thesis created a re-tuned optimisation system. The system has considered two important parameters, network context and network performance, to determine the third parameter routing protocol. These parameters are not constant; the system can add any new (recent) parameters or delete any unwanted (old or less important) parameters to/from the parameters list and the model will update accordingly, as described in Section 9.4.1.3. The system can also re-tune the priorities for each element in the fitness equation based on the user requirements. Section 9.4.1.5 regarding future work explains this characteristic in greater detail. Given the aforementioned advantages, the proposed system can be implemented to solve other problems in communication as well.

9.4 Future Research

The I-MAN routing protocols optimisation system achieved in this thesis has proved its efficiency through the case study results. However, more effort should be involved to develop and expand the system for use in other areas. The work in this thesis opens up research on various interesting issues and fields, as discussed below.

9.4.1 Short Term Future Research

For short term future research, the following issues need to be explored. A better system will be produced as a result of further investigation and study of the parameters that are listed in this section.

9.4.1.1 Models Range

Obviously, the more models the I-MAN routing protocols optimisation system has, the more accurate the system decision will be. The system infers the network performance based on a range of trained models. The selected ranges for the network size and the average mobility can be extended so that the MANET models can be upgraded to represent larger and faster networks.

9.4.1.2 Update Models

The network performance models in the I-MAN case study scenario were not updated. To develop the models to represent online network performance, the models should be updated. Models can be updated on a regular basis by first storing the network performance data during the network operation and then producing new, updated performance network models in the off-peak time. Updating the models frequently will result in representative models that have new information required by the intelligent optimisation unit. Any modification to the models should match the changes in the network performance.

9.4.1.3 Extend the Network's Parameters

In this thesis, the I-MAN routing protocols optimisation system is based on three important network elements: the context-aware parameters, the output performance parameters, and the routing protocols. The extension for each element is explained as follows:

a. Context Parameter

The optimisation system decision relies on two context parameters: network size and average mobility. More parameters could be considered for selecting the most suitable routing protocol for a specific situation; for example, various types of *Entity mobility* models. In this thesis, one type of Entity mobility model, the Random Walk Mobility Model, has been implemented. Other Entity mobility models could be implemented to evaluate the mobility models effect on the network, such as the Random Waypoint (with pause time) and Random Direction [2] models.

b. The Performance Parameter

Any new parameters that represent the network performance, such as battery life or power consumption, could be added and integrated in the cost equation for each protocol.

c. The Routing Protocols

More routing protocols could be included in the intelligent optimisation unit list. This list could also be used as a library that includes all the known routing protocols in MANET, for both the state-of-art routing protocols and the classical (traditional) routing protocols.

9.4.1.4 Add More Elements

This thesis relies on context-awareness to judge the network performance. In the future work, more elements could be added, such as:

a. Application type (packet type)*:* The packet type could also added as a second element, Thus the intelligent optimisation system will choose the optimum routing protocol depending on both the network context and application; and then run multi-simulation scenarios. Each with a particular application. Models could be created for these individual applications to represent the simulation data collected earlier.

In addition, besides creating models for the individual applications, there could also be simulation scenarios and models for combining two or more applications running at the same time; such as models for video, voice conferencing, email, file transfer, and/or any new invented application type that proved its influence on the network performance in future.

b. Routing activity is another important parameter that could also considered in situations, for instance, in which nodes are exchanging exceptionally more information between each other than usual. Moreover, route requests may be a constant operation in the network and, consequently, could be improved by one of the routing protocols considered.

c. ***Congestion*** might be added as an input parameter that show the network performance when the network size varied for a constant network area.

d. ***Data rate*** could also be added as a parameter in the network performance. Models could be made from the simulation data that represent the network sending its packets at different data rates.

Besides the parameters mentioned above, the search to discover further factors should continue. The aim is to create a list that contains all the parameters that affect the network behaviour.

9.4.1.5 User Requirement

In this thesis, the results were presented for the intelligent optimisation system decision following the network topology changes, assuming that there is no requirement for the user. User requirements will prioritize the performance parameters and give more weight to one parameter than the other. The Optimiser can respond to the user requirement and gives extra options to improve the network by prioritizing the performance. Therefore, the cost function in Equation (7.4) will be modified to become the Equation (9.1) below:

$$\text{Cost function} = \frac{r \times (RA)^2 + dd \times (Data\_drop)^2 + l \times (Load)^2 + d \times (Delay)^2 + th \times (1 - Throughput)^2}{5} \tag{9.1}$$

Assuming *r*, *dd*, *l*, *d*, and *th* are the priority parameters for RA, data drop, load, delay, and throughput, respectively, where *r*, *dd*, *l*, *d*, and $th \leq 1$. In this case study these parameters were assumed to be equal to one, thus allowing the network performance “equal opportunity.” However, if the priority parameter’s values differentiated, each performance parameter will be given its own priority level in the cost equation and thereby affect the PSO Optimiser’s decision. As such, more case studies should be carried out to show the intelligent optimisation system results of combining user requirements with network topology changes.

9.4.1.6 List of Intelligent Nominees

In the I-MAN case study scenario, the entire computation process load for the intelligent optimisation system is based in the Intelligent node. In the case of Intelligent node failure, the network nodes will nevertheless continue to send Topology packets containing their current context without any reply from the Intelligent node. This situation leaves the network operated as a normal network (before activating the I-MAN routing protocols optimisation system), with an extra overload from the periodic Topology packets.

Therefore, the suggested solution will be to undertake another case study that implements a simulation scenario in which the Intelligent node, and all the nodes embedded in the intelligent optimisation system, have a *list of nominees* containing all nodes capable of substituting for the Intelligent node if it fails. These nodes could also be called the standby or backup nodes. In this scenario, there should be an extension in the node's Topology packets. This extended field should be called the *ability field*. It will take a one-bit space in the packet. This one bit will be like a flag with two options, 1 or 0. If the network node is still able to supervise the network, the flag will be on (ability field equal to 1); whereas if the network node does not has the capability to supervise the network for a particular reason, such as the node dose not have sufficient battery, then the ability flag will be off (ability field equal to 0). Thus, after the network nodes send their modified periodic Topology packets to the Intelligent node, the node based on those Topology packets will compare its stored *list of nominees* and update it with the nodes that are still capable of supervising. The Intelligent node will order the nominee node based on a "first come, first serve" strategy. The first nominee node on the list will be the first the Intelligent node receives its Topology packets from, with the ability flag 1. With the same strategy, the Intelligent node will fill the rest of the list. As a result, a new list of nominee nodes will be created in the Intelligent node, then it will be attached to the Decision packets for the nominees ID addresses in MANET. This means that all the network nodes will have an updated list of the Intelligent node's nominees. If, however, the Intelligent node fails suddenly, then the network nodes will have to wait for a Threshold time. For example, this Threshold time could be equal to three times the Topology packets' periodic time. After the Threshold time, the network nodes will send their periodic packets to the first nominated node in the network nodes' nominee list. Also, if the Intelligent node is planning to leave the network, then it will order its last Decision packets to be sent to the first nominated node in the network nodes nominee list. More scenarios representing the solution mentioned in this section could be considered to evaluate this case.

9.4.1.7 Partitioning the Network or Dropping the Protocol

More simulation scenarios could be considered in which not all nodes have the three protocols embedded in them; that's means, not all nodes have the capability of running the same routing protocol. There are two possible decisions that could be made in this case, either: a) the protocol that is not common to all nodes is not to be considered; or b) the network is divided into two routing areas. A comparison should be made to find out which solution is more efficient and beneficial to network performance.

9.4.1.8 Hidden Nodes

More simulation scenarios should be ran with the assumption of a network with hidden nodes; for example, one simulation with the assumption that some of the nodes are not receiving the Decision packets sent by the Intelligent node, and another with the assumption that the Intelligent node is not receiving all network Topology packets.

9.4.1.9 AI Technique

In this thesis, many AI techniques have been implemented, including ANN, NF, GA, and PSO. Other AI optimisation techniques, such as the Ant colony and the Honey Bee, could be implemented, evaluated, and compared with GA and PSO.

Whereas the intelligent optimisation system herein embedded NF and PSO, other intelligent systems could also be created using any of the previous AI techniques, such as ANN and GA. These new systems can then be compared against the I-MAN routing protocols optimisation system.

9.4.2 Long-Term Future Research

In long-term future research, the following issues need to be explored.

9.4.2.1 Add Routing Protocol Classification List to I-MAN System

In this research, the I-MAN protocol switches between routing protocols with different routing philosophies. For example, in the I-MAN case study, the network nodes switch from a reactive protocol (DSR or AODV) to a proactive protocol (OLSR), and visa versa. If the node was using one type of routing protocol, for example, proactive, and switches to another type, for example, reactive, it will loose its routing table. To employ the new optimum routing protocol, then, the nodes should establish a new routing table. This operation will involve sending many control messages to gather and collect the information data about its neighbours and sort them in their routing table. This is a loss for the network nodes' computing time and energy, as their battery life has been wasted and the network was over a continuance load. Additionally, this process will start all over again whenever another switch occurs. As such, a solution has been suggested in this section to modify the original I-MAN routing protocols optimisation system and overcome this problem. That is adding a classification list to the I-MAN system. This list contains various classifications for the routing protocols (similar to the taxonomies mentioned in Chapter 2), as the Optimiser will depend on them to reach its decision.

The modification here involves switching between the protocols that have similar characteristics. The routing protocols listed in the Intelligent node (Optimizer) should have the classification for the routing protocol, according to the characteristics. The PSO Optimizer will select the routing protocol that has similar characteristics to the previous operated protocol. This solution also gives strength to the system as it will narrow the area searched by the Optimizer's to select the optimum protocol.

In this case, another selection criteria is added, which is to select the optimum protocol with the same network characteristic. For example, the Optimizer prepared classified the routing protocols according to the network characteristics below:

(a) Routing philosophy: reactive, proactive, or hybrid routing protocols.

(b) Network structure: flat, hierarchical, or Geographical Position Information routing protocol.

(c) Casting packets technique: unicast, or multicast routing protocol.

(d) Network routing metric: hop number or link stability.

For instance, if a reactive routing protocol in operation degraded because of the context change, the intelligent Optimiser will have to replace it with another reactive routing protocol from its classification list. The protocols from the same routing philosophy will share the same routing table, such that if a switching occurs the node will not loose it routing table, but instead be used by the new routing protocol. This solution will improve the situation of the network nodes as they will hold and reuse their routing tables when deploying the I-MAN intelligent optimisation system in their network.

9.4.2.2 Context-aware routing protocol

Creating a context-aware routing protocol is the other way of solving the problem, as mentioned in the summary. This solution does not require a routing protocol classification list. The intelligent optimisation system will not have to distinguish between the protocols and classify them according to their characteristics. This solution is more complicated than the first one as it depends on modifying the network node routing table to be used by all of the routing protocol types. This means that the node routing table is flexible and can be adopted by any type of routing protocol. For example, if a reactive routing protocol is operating and the node switches to a different protocol in the routing philosophy, such as proactive or hybrid, then the old node's routing table could still be used. In this way, there will be fewer overloads and less network energy expended because all neighbouring node information will be saved.

9.4.2.3 Wireless Mesh Network

The network scenario would be more realistic and the energy problem will be solved if the intelligent optimisation system is part of a mesh network. Obviously, the protocols the system includes will be WMN protocols [3], with the system embedded in one of the backbone mesh routers connected to the MANET. If the mesh router is a station node (for example, desktop computer), then it has sufficient power and computation capability to supervise the network; therefore, it will reduce the probability of encountering the single-point-of-failure problem.

9.4.2.4 Cognitive Network

The cognitive network includes a cognitive process that implements adaptation and learning techniques [4]. The network implemented in the proposed system is an active network that can be developed for a cognitive network by improving the learning technique (modelling part) in the system, as the adaptation component is already equipped for integration. Developing the learning technique will be achieved by updating the network performance models online.

9.4.2.5 Intelligent Transportation Systems

Vehicular communications are a cornerstone of future Intelligent Transportation Systems. By enabling vehicles to communicate with each other via Inter-Vehicle Communication, as well as with roadside base stations via Roadside-to-Vehicle Communication, vehicular networks will contribute to safer and more efficient roads. The network also will provide timely information to drivers and concerned authorities [5].

Therefore, Vehicular Ad hoc Networks (VANETs) [6] that allow vehicles to form a self-organised network without the need for permanent infrastructure are an interesting area in which to apply the proposed system. The result will be an Intelligent Transportation System, keeping in mind that VANET routing protocols are developed from popular unicast and multicast MANET routing protocols.

9.4.2.6 Internet of Things System

The Internet of Things (IoT) is a new concept that is rapidly gaining considerable attention in modern wireless telecommunications [7]. The idea behind the IoT is based on interactions between varieties of objects, or “things,” around us. These things have their own unique ID address and are able to cooperate with their neighbours to reach common goals. IoT is created from three oriented visions: *Things-Internet –Semantic*, where the word Internet represents any wireless telecommunications.

The proposed intelligent system acts as an actuator, therefore, it could represent the “Things-”oriented vision of IoT. The system also implemented in MANET, thus it represents the “Internet-”oriented vision of IoT. Therefore, to develop the proposed system to represent the Internet of Things, it should integrate the “Semantic-”oriented vision such as the semantic technologies.

9.4.2.7 Real Test Bed

This thesis implemented the intelligent optimisation system by simulation. To put this system in a real test bed, the system will require efforts in modification and development to match the realistic situation.

9.4.2.8 Expanding the System

The system was designed to combine performance parameters into one equation that will determine the optimal routing protocol for a given situation and then trigger that protocol in the network; this solution could be applied to other computing problems as well. The possibility of expanding this optimisation system to other layers in networking systems, and also to other fields of computer science and informatics, should be studied.

9.5 References

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