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A New Environment-Aware Framework For The Research of Mobile Ad hoc Networks

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DECLARATION

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other university or any other institution of learning.

Mr. Gang Lu

15th May, 2008

Dedicated to my family,

My parents: Chengzhang Lu and Yvhui Wu

My wife: Eva Xu

ABSTRACT

The purpose of this research is to improve the performance of Mobile Ad hoc NETworks (MANET) by using simulation. A new self-positioning algorithm was proposed by which the mobile nodes can obtain their locations with and without the existence of Global Positioning System (GPS). This algorithm was integrated into a new routing protocol Location-Label Based Routing (LLBR) protocols. Unlike other location-based routing protocol, LLBR makes it possible to enhance without the aid of GPS, the routing performance using the local coordinates system. It was noticed that the mobility of mobile nodes could have significant influence on the performance of a network and the environment also must be considered carefully as MANET can be deployed anywhere. The need for a framework to better study MANET was identified. The research then moved on to develop an Environment-Aware Framework for the research of MANET. A new Environment-Aware Mobility (EAM) model in which the mobility of mobile nodes can be impacted by the environment was proposed, and two particular sub-models: the Route Mobility Model and the Hotspot Mobility Model targeted at road and hotspot environment, respectively were also proposed to show the flexibility of EAM. Two special mobile ad hoc networks, the RoadLamp-aided Inter-Vehicle Communication (IVC) system and the Bus-aided IVC system are proposed to help improve the performance of the deployed networks in city environments. A set of tools were developed to construct the environment, model the mobility of mobile nodes, visualise the movements and evaluate the performance of the network. The simulation results have shown that network performance can be enhanced by taking advantage of the self-positioning algorithm, the framework which takes the environment into account in simulation, enables more realistic MANET to be studied and evaluated and also proves that the environment must be carefully considered together with the mobility of mobile nodes in the research of MANET. To show the expandability of the framework, a mobility-concerned emulator was also introduced.

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LIST OF ABBREVIATIONS

2-D	2-Dimention
3-D	3-Dimention

A

AP	Access Point
AODV	Ad hoc On Demand Distance Vector routing
APS	Ad Hoc Positioning System
AoA	Angle of Arrial
AA	Accessible Area
AS	Application Server

B

BER	Bit Error Rate
BTMA	Busy Tone Multiple Access
BS	Base Station
BN	Bus Node

C

CTS	Clear To Send
CBRP	Cluster-Based Routing protocol
CBR	Constant Bit Rate

D

DSSS	Direct-Sequence Spread Spectrum
DMAC	Directional Medium Access Control
DNAV	Directional Network Allocation Vector
DSDV	Destination Sequenced Distance Vector
DIFS	Distributed Inter-Frame Space
DSR	Dynamic Source Routing
DREAM	Distance Routing Effect Algorithm for Mobility
DFWMAC	Distributed Foundation Wireless Medium Access Control
DIFS	Distributed Inter-Frame Space
DBASE	Dynamic Bandwidth Allocation/Sharing/Extension
DIB	Direction Indicator Byte
DFS	Depth-First Search
DR	Delivery Rate

E

EAM	Environment-Aware Mobility
EO	Environment Object

ELF	Environment Layout File
ECF	Environment Configuration File
EED	End-to-End Delay

F

FHSS	Frequency-Hopping Spread Spectrum
FDD	Frequency Division Duplex
FSPL	Free Space Path Loss
FIFO	First In and First Out

G

GPS	Global Positioning System

H

HIPERLAN	HIgh PERformance Local Area Network
HMN	High Mobility Node

I

IVC	Inter-Vehicle Communication
ISM	Industrial, Scientific and Medical
IFS	Inter-Frame Space
IAMB	Intelligent Autonomous Mobile Bridges

J

J2EE	Java 2 Platform Enterprise Edition

L

LLBR	Location-Label Based Routing
LAR	Location-Aid Routing
LCS	Local Coordinate System
LRA	Local Routing Algorithm
LMN	Low Mobility Node
LAN	Local Area Network

M

M2MI	Many-to-Many Invocation
MANET	Mobile Ad Hoc NETworks
MN	Mobile Node
MAC	Medium Access Control
MACA	Multiple Access with Collision Avoidance
MS	Mobile Station
MP	Mobile node Positioning

N

NAV	Network Allocation Vector
NLOS	Non-Line-of-Sight
NAA	Non-Accessible Area
NORAA	NORmal Accessible-Area

O

OSI	Open Systems Interconnect
ODF	Obstacle Description File
OCF	Output Configuration File

P

P2P	Peer-to-Peer
PDA	Personal Digital Assistant
PAN	Personal Area Network
PS	Priority Scheduling
PIN	Personal Identification Number

Q

QoS	Quality of Service

R

RPGM	Reference Point Group Mobility
RIP	Routing Information Protocol
RI-BTMA	Receiver Initiated-Busy Tone Multiple Access
RTS	Request To Send
RCS	Reference Coordinate System
RRA	Remote Routing Algorithm
RN	Restricted Node
RO	Routing Overhead

S

SIFS	Short Inter-Frame Space
SSA	Signal Stability-based Adaptive Routing
SN	Static Node
SVG	Scalable Vector Graphics

T

ToA	Time of Arrival
TDoA	Time Difference of Arrival
TDD	Time Division Duplex
TTL	Time To Live

TERRAIN	Triangulation via Extended Range and Redundant Associated of Intermediate Nodes
TCP	Transmission Control Protocol

U

UML	Unified Modeling Language
UDP	User Datagram Protocol

V

VPN	Virtual Private Network

W

WRP	Wireless Routing Protocol
WLAN	Wireless Local Area Network

X

XML	eXtensible Markup Language

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Chapter 1: INTRODUCTION

A Wireless Local Area Network (WLAN), or wireless LAN can be defined as the linking of two or more computers without using wires. In a WLAN, users are able to move around in a broad area while still connected to the network. Because of the ease of installation and the flexibility, the WLAN has been widely accepted in the office, home and even some public places such as café, pub etc.

There are two types of wireless local area networks. The infrastructure-based wireless LAN, normally called as Wi-Fi which is a system that enables the mobile devices (mobile nodes) to communicate with each other wirelessly with the aid of a special device called an Access Point (AP). All the packets sent by the mobile nodes have to be forwarded by the AP, i.e. the AP acts as the routers used in a conventional wired network. The interconnection of these APs forms a larger network. The second type of wireless LAN is an infrastructure free network. It can be considered as a Peer-to-Peer (P2P) wireless network where two mobile nodes within antenna working range of each other can have the direct communication without the involvement of the APs. This type of WLAN is also defined as a wireless ad hoc network or Mobile Ad Hoc NETworks (MANET).

Mobile ad hoc networks are the focus of this thesis. Since there are no dedicated routing devices existing in a mobile ad hoc network, each mobile node has to take two roles, the packet sender/receiver and also the packet forwarder, namely the router. Therefore, each mobile node should implement a routing algorithm and maintain the routing information in order to communicate with other mobile nodes.

Wireless networks and especially mobile ad hoc networks are very challenging for the following reasons. The channel bandwidth is limited; the signals may suffer high contention and attenuation; the mobility of mobile nodes and the environment can cause frequent changes in network topology, etc. Section 1.1 addresses these problems in more detail.

Section 1.2 outlines the aims and objectives of this thesis, concentrating on several novel works which attempt to improve the network performance by using a location-based routing protocol based on a self-positioning algorithm. It also proposes a more realistic mobility model which reflects the complex wireless environment and develops a mobility-concerned flexible and configurable framework.

The aforementioned algorithms, concepts, approach and mechanisms are discussed in greater detail in the subsequent chapters of this thesis. The structure of the thesis is described in Section 1.3.

1.1 PROBLEM DESCRIPTION

Mobile Ad Hoc NETworks (MANET) consist of wireless mobile hosts which can communicate with each other in the absence of a fixed infrastructure. The mobility of Mobile Nodes (MN) can easily cause the topology to change and consequently result in frequent updating of routing tables. The limited bandwidth compared to wired networks is another key factor that needs to be considered when investigating packet routing algorithms. Researchers have proposed several approaches, such as the Ad hoc On Demand Distance Vector routing (AODV) [1], the Dynamic Source Routing (DSR) [66] etc, to solve the routing related issues. Among them, the Location-Aid Routing (LAR) [73] algorithm and Distance Routing Effect Algorithm for Mobility (DREAM) [68] differ in that they can take advantage of the location information of each node in order to reduce the routing area and route discovery overheads. Figure 1.1 demonstrates the idea that using the location information can enhance the routing performance. Node *S* is the sender and Node *D* is the destination. Figure 1.1(a) shows how the packet is transmitted if there is no particular routing protocol implemented. In this case, all mobile nodes including the node *C*, *E* and even node *F*, *G*, *H* have to be involved with the packet forwarding even those which are far away from the destination nodes. Figure 1.1(b) demonstrates how the performance can be enhanced with the aid of locations of mobile nodes. The packet is sent towards the destination node and only the nodes located in certain area close to the destination will be responsible for the packet forwarding. So the nodes *C*, *E* and *F*, *G*, *H* may not be intermediate nodes to forward the packet.

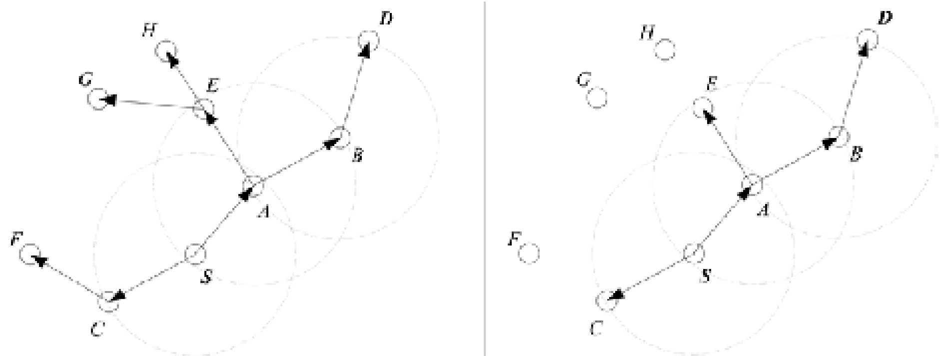


Figure 1.1(a) Illustration of the routing procedure in mobile ad hoc networks (no particular routing protocol implemented)

Figure 1.1(b) Illustration of the routing procedure in mobile ad hoc networks (with location based routing protocol implemented)

FIGURE 1.1 ILLUSTRATION OF THE ROUTING PROCEDURE IN MOBILE AD HOC NETWORKS

However the main problem here is that all of these so called location based routing protocols assume that all of the nodes can receive a Global Positioning System (GPS) signal, with which their position is detected. However this assumption is not realistic for most mobile ad hoc networks. MANET is capable of being constructed anytime and anywhere, but the GPS signal could be very weak in bad weather conditions and might be completely unavailable in indoor environments. Therefore in order to enhance the network performance, an improved algorithm that is capable of using the location information regardless of the presence or not of GPS signal is required.

Self-organization is the essential characteristics of this mobile wireless network. The mobile nodes within the network can be any moving or static objects equipped with an antenna. Due to the movement of the mobile nodes, the networking performance might differ significantly. In general, the lower the mobility of the mobile nodes, the higher and more stable the performance. The reason is that the lower mobility normally causes more constant network topology. This lets the protocols spend less effort on some network maintenance jobs such as route repair, route discovery etc, and also reduces the risk that the network is unexpectedly partitioned. Therefore, the mobility of mobile nodes becomes one of the key topics in mobile ad hoc network research. There have been proposed many mobility models that can be used to simulate the movements of the mobile nodes in different situations. Defining the mobility model is mandatory when simulating a mobile ad hoc network. Most of the research to-date assumes that the network is deployed in an open area where the mobile nodes can theoretically move to any location inside. The influence of the environment has been ignored. As a matter of fact, the self-organisation of mobile nodes not only means the mobile nodes can move with a certain mobility pattern, but also implies the mobile nodes can adjust their movement characteristics depending on the environment they are located. In a real environment, the mobile nodes may be human beings walking in a mall or gallery at low speed, a bus moving in a city, a car running on a highway, a roadlamp (a mobile node with zero speed) standing along the street or even animals moving in a natural environment. It is common for a mobile node to change its behaviour, for example a car has to slow down when it drives off the highway. In other words, the mobility of mobile nodes should be modelled with the concerns of the environment. If this is done, the results from the network simulation will better reflect the real situation. Inter-Vehicle Communication (IVC) systems are considered as special cases of mobile ad hoc networks where the mobile nodes are composed of different types of vehicles. IVC systems are deployed in particular environments, for example in a city. There has been some research in this area in order to find a better solution to enhance network performance. However, since these methods do not model the city environment, such as the high possibility of a signal being blocked by a building, the contribution of those works is limited and new solutions need to be explored.

Network simulation is used to measure the value of the proposed research works. Unfortunately none of the popular simulators provides such a realistic mobility model, most of them still use a very basic mobility model, such as the Random Waypoint model. Most of the tools integrated into these simulators assume that the networks are deployed in an open space and the details of the environment are completely ignored.

What's more, once environmental factors are introduced into the mobility model, many new mobility models will be derived from the conventional ones for various environments. This brings another issue which is that none of the existing tools developed for modelling the mobility of mobile nodes are not scalable enough to deal with this requirement.

It is very common in the mobile ad hoc network research to use exactly the same network configuration and the same protocols in each network layer implemented by the mobile nodes, however the network performance obtained from the simulations turns out to be significantly different. In most cases, the difference is caused by the mobility of mobile nodes because the movement pattern of each mobile node is calculated randomly in each simulation. The best way to diagnose the potential weakness of the protocol simulated is to 'see' what is happening during the simulation, i.e. to know for what topology the protocol fails. How to visualize the movement of each mobile node becomes a very interesting and important topic, but the problem is that none of the existing mobility modellers come with tools that help the researchers to better understand the network and to further improve their research.

1.2 AIMS AND OBJECTIVES

Based on a thorough understanding of the properties of mobile nodes in mobile ad hoc networks, the aims of this thesis are to propose a new approach to help other researchers better evaluate their work and efficiently improve the performance of the mobile ad hoc networks. The network performance can be enhanced by introducing a new location based routing protocol; By taking the environment factors into account, particular mobile ad hoc networks deployed in complex environments can be better studied and new solutions to improve the network performance can be explored; A new approach to simulate mobile ad hoc networks with more emphases on the mobility models in a relevant environment will help to fulfil the aims of this research and also help others obtain more valuable information from the network simulation.

In order to achieve these ambitious aims, a number of objectives must be first set and later evaluated. This helps concentrate on the design of the specific algorithm, protocol, methodologies etc, by picking up appropriate knowledge and technologies, and then finally assess the outcomes. The following are the main objectives of this study:

1. Propose a new algorithm for the calculation of the location of the mobile node.

   A self-positioning algorithm helps the mobile nodes in a mobile ad hoc network to compute their locations. To be more precise, without the help of the GPS, this distributed algorithm will be able to generate a local coordinate system and also help each mobile node compute its own coordinates in this system. If part of the network can receive the GPS signals, the algorithm should help the mobile nodes which have no access to the GPS convert these locations in local coordinates to the location of the GPS system.

2. Propose a new location based routing protocol which integrates with the new positioning algorithm.

   – The new routing protocol essentially uses the locations of mobile nodes to optimize the routing of data packets. Unlike other location based routing protocols, this protocol will fully integrate the self-positioning algorithm and use the resulting local coordinates system to reduce the routing area, i.e. only the mobile nodes that reside in the same direction as the destination node to the source node will be used in the packet forwarding.

3. Develop an environment-aware framework which introduces a new mobility model which not only models the characteristics of the movements of mobile nodes but also take into account the influence of the environment.

   – A novel realistic mobility model is required which incorporates the environment where the mobile ad hoc network is deployed. The movements of the mobile nodes are not only decided by themselves but also affected by the environment. The real environment needs to be carefully studied in order to propose a new approach to present diverse environment objects that are the basic objects used to form the entire environment. The impact of environment objects has to be defined and implemented in the new mobility model.

By taking advantage of the new model and also to demonstrate its scalability, several sub-models need be proposed so that complex environments can be constructed at some particular cases.

4. Use the new proposed the environment-aware mobility model to investigate a special mobile ad hoc network, the Inter-Vehicle Communication (IVC) system in city environment and explore new solutions for the improvement of its performance.

- The proposed new mobility model is expected to be able to construct a more realistic city environment to enable the study of the performance of IVC system. New solutions to improve the performance of IVC systems in city environment can also be explored.

5. The mobility models proposed need be implemented. In the framework, develop a set of flexible and configurable simulation tools which can be used for the simulation of the aforementioned algorithm, protocol and approach.

- In the proposed environment-aware mobility model, the framework can be used to implement environment objects, such as Route, Hotspot etc, in order to present a complex realistic environment. The resulting environment can be read by the mobility simulator and influence the mobility of the mobile nodes during the simulation.

  In order to help the researchers better construct the simulation environment and easily verify the simulation results against the mobility of the nodes and the environment, the framework needs to provide the capability to visually monitor the movements of the mobile nodes.

  The framework must be able to model the environment-aware mobility, and it must also be able to be used as a conventional mobility modeller. It should also be designed with concerns of scalability to allow researchers to develop their own models which are aware of the impact of the environment.

  The framework should provide a set of evaluation tools. These tools should be able to be used to measure two types of metrics, connectivity-related metrics and routing-related metrics.

6. All the algorithm, protocols and mobility models proposed are required to be simulated and evaluated. The simulation results need be presented and analysed.

7. By taking advantage of the environment-aware feature of the framework, expand the network simulation to the network emulation for further study of mobile ad hoc networks.

The aforementioned objectives will be addressed in detail in the rest of thesis. Since the work done in this thesis crosses over a multitude of research areas in the research of mobile ad hoc networks, from self-positioning algorithms, routing protocols, mobility modelling, inter-vehicle communications systems to the development of a framework for network simulation and emulation, an overview of these topics is discussed in each chapter and how they are related to this thesis are given in next section.

1.3 THESIS STRUCTURE

The following chapters give the detailed discussion on the ideas, algorithms and solutions mentioned in this chapter.

Chapter 2 provides a comprehensive review of relevant issues related to mobile ad hoc networks. The properties of mobile nodes are studied from various aspects which cover the physical and environmental issues, radio, energy, antenna, mobility, protocols-related and the topology. Mobile ad hoc networks have been one of the hottest research topics for years, but rarely have they been studied from a different angle, from the perspective of the elements which form the networks, namely the Mobile Nodes. The physical specifications, the signal specification, self-organisation characteristics, the mobile pattern etc drive the direction of the researches.

The background review of mobile ad hoc networks in Chapter 2 shows that this area contains a very broad set of topics worth discussion. In our work, several most important properties, the self-organisation, mobility model and network simulation are the main focus of our research and are addressed in detail in later Chapters.

Chapter 3 focuses on the positioning of mobile nodes and location based routing. The locations of the mobile nodes can be usefully used for running and using the mobile ad hoc networks. In GSM network, the base stations and their fixed locations can be used for the calculation of any mobile node, which is not possible for the infrastructure-free mobile ad hoc network; The GPS system could be a good approach for the detection of locations if the mobile nodes are all equipped with GPS receivers. However since there would be many situations for the mobile ad hoc networks where the GPS signal can not be perfectly received by every node, a better solution is required. Chapter 3 defines a new algorithm for the positioning of mobile nodes, which can operate in both GPS-free and GPS-aided environments. GPS coordinates can be calculated if two or more neighbouring nodes have GPS based coordinates, otherwise a relative local location is provided instead, which is sufficient for the routing algorithms. A new location-based routing protocol is also proposed which integrates this algorithm so that the locations of the mobile nodes become the factors which contribute to the performance of the mobile ad hoc networks.

In Chapter 4 describes the essential work of the environment-aware framework for the simulation of mobile ad hoc networks and a novel realistic mobility model, Environment-Aware Mobility (EAM) model is proposed. The new model is incorporated with the aspects of environments where a MANET is deployed. The Environments are represented by introducing some environment objects, such as a Route, a Junction, an Accessible Area, and a Hotspot etc. Signal-blocking issues are also covered in this model by introducing ClosedAreas whose boundaries are considered to be obstacles with no radio penetration. Two sub-models of EAM, Hotspot model and Route model are also proposed in order to handle some complex environments. The Hotspot model is proposed to describe the movement of the mobile nodes when attractive places exist in the simulation area. The Route model can be used to construct some complex environments such as a city area. In this chapter, a new IVC mobility model based on the Route Mobility model is also proposed. Unlike others, this IVC model takes more realistic factors into account. To help investigate the performance of certain mobile ad hoc networks in more complex environments, two particular IVC systems in city environment, the RoadLamp-aided IVC system and the Bus-aided IVC system are studied.

In Chapter 5, a scalable environment-concerned mobility modeller is developed and detailed as a part of the framework. The output of this modeller can be used by the Network Simulator 2 (ns2), and can also help the visualization of the movement of the mobile nodes in the simulation. Several performance evaluation tools are also developed to measure the network performance in the mobility-concerned environment. The working mechanism and usage of these tools have been included in the framework and the approaches are all detailed in Chapter 5.

All the simulation results are presented in Chapter 6. As the work described in this thesis focuses on several correlated topics of mobile ad hoc networks but with different emphases, different methodologies are used for the evaluation of each topic. These methodologies are described in detail along with the analysis of the results.

The environment-aware framework proposed for the simulation of mobile ad hoc networks can be also expanded to the network emulation. The design of the mobility-concerned emulator is described in Chapter 7.

Finally, Chapter 8 summarises the contributions of this thesis, draws conclusions and proposes the future work.

Chapter 2: THE PROPERTIES OF MOBILE NODES IN MOBILE AD HOC NETWORKS

2.1 INTRODUCTION

A Mobile Ad hoc NETwork (MANET) is an autonomous system of mobile nodes. No fixed infrastructure exists in the configuration of the network, which is the feature that distinguishes it from other communication systems. Mobile nodes use certain types of antenna to communication with each other, and the communication between the nodes is only possible when they are located in each other's antenna radio range. To let mobile nodes far apart communicate with each other, a so called 'relay' method is used in MANET. Then, any mobile node will have two roles: a normal role and a router role. In other words, the packets will be delivered by the nodes in the route(s) until they get to the destination. Unlike the conventional network systems (wired networks and infrastructure-based wireless communication networks), MANET has many more factors which need to be considered, such as the variable topology, the network environment, the properties of the Mobiles Nodes (MNs), etc.

In this Chapter, the components of MANET, Mobile Nodes are studied. All the aspects which are related to the MNs are reviewed in order to obtain better understanding of mobile ad hoc network. Most of these properties described here could highly influence the overall performance of MANET.

Considering the latest technology in the WirelessLAN (WLAN) industry, we think of wireless PCMCIA cards, Personal Digital Assistant (PDA) and some latest mobile handsets as the most popular wireless equipment nowadays. Thus, these gadgets are described here to represent typical MNs. In the rest of this chapter, the properties of mobile nodes are studied from different aspects which cover the physical and environmental issues, radio, energy, antenna, mobility, protocols-related and the topology.

A thorough understanding of the mobile ad hoc networks can be achieved based on the discussion of these properties of mobile nodes. The performance of MANET highly depends not only on the mobile nodes themselves but also on the environment where the network is deployed. Some important properties and issues will be further discussed in Chapters 3, 4 and 5, together with the solutions, research tools and simulation-based evaluation.

2.2 PROPERTIES OF A MOBILE NODE

2.2.1 Physical and Environmental Specification

Mobile ad hoc networks have been promised to be the most flexible wireless network which can be deployed anytime and anywhere. With the increasing data rate and infrastructure-free characteristic, mobile ad hoc networks are able to be used for more environments and more mobile applications can be developed than the wired network and even the Personal Area Network (PAN). Mobile Internet can be accessed by using Personal Digital Assistant (PDA) of Wi-Fi enabled mobile phones; multimedia wireless can be easily set up in home/office network; mobile office, real-time multimedia information will be available in public area; military communication equipments will be used in battlefields, and so on. Mobile ad hoc networks have become a very important part of the modern life. In order to bring the best convenience to the end users, the mobile nodes are required to be small, light, and environment-independent. Some popular wireless devices including wireless PCMCIA card, PDA and mobile phones are studied. Table 2.1 gives the physical and environmental specification of some best sale devices.

A wireless PCMCIA card can provide a Desktop PC or a laptop with mobile ad hoc network access, and the latest modules of PDAs and even mobile phones shown on the Table2.1 are getting much more popular than 5 years ago. The physical existence of these small wireless gadgets indicates the brilliant future of the mobile ad hoc networks. With the rapid development of chip design technology, these wireless nodes are expected to be even smaller, thinner, more portable and suitable for varied environments. More and more traditional facilities could be equipped with wireless-supported chips and gadgets, e.g. the cars, trams, buses, traffic lights etc in the both indoor and outdoor environments.

The future of wireless ad hoc network is exciting, and it also implies that the research of this type of wireless network is also very challenging because of the very different properties (velocity, individual behavior, group behavior etc) which have to be dealt with in the research.

TABLE 2.1 THE COMPARISON OF PHYSICAL AND ENVIRONMENTAL SPECIFICATION OF MOBILE GADGETS

Type	Module	Physical Specification (mm)		Environmental Specification	
		Dimensions (mm)	Weight (g)	Temperature	Humidity
Wireless PCMCIA Card	OriNOCO ComboCard	117.8 x 53.95 x 5	55	0 to $70^{\circ}C$	0 to 95%
	Cisco Aironet350	111 x 54 x 3	45	-30 to $70^{\circ}C$	10 to 90%
	3Com 3CRWE62092B	105.2 x 54 x 5	N/A	0 to $50^{\circ}C$	10 to 95%
	Enterasys RoamAbout	117.8 x 53.95 x 8.7	N/A	0 to $55^{\circ}C$	0 to 95%
	AmbiCom WL1100B	95 x 54 x 5.8	50	0 to $50^{\circ}C$	0 to 95%
	Compaq WL110	117.8 x 53.95 x 8.7	55	0 to $55^{\circ}C$	0 to 95%
	LinkSys WPC11	115 x 54 x 7.5	47	0 to $55^{\circ}C$	0 to 90%
	Usr 2210	121.9 x 52.3 x 3.17	40	0 to $50^{\circ}C$	0 to 70%
PDA	iPaq 4150	113.6x70.6 x 13.5	132.4	N/A	N/A
	Palm T|X	78.2 x 120.9 x 15.5	148.8	N/A	N/A
Mobile Phone	Dopod 838 Pro	112.5 x 58 x 21.95	176	N/A	N/A
	Nokia-N95	99 x 53 x 21	120	N/A	N/A
	Nokia-E61	117 x 69.7 x 14	144	N/A	N/A
	iPhone	115x61x11.6	135	N/A	N/A
	BlackBerry	114 x 66 x 14	134	N/A	N/A

2.2.2 Radio Specifications

In this section, the topics related to the radio specifications are discussed, including:

- **Frequency:** In order to avoid the issues with international frequency license, MNs are normally designed to operate on Industrial, Scientific and Medical (ISM) Frequency Bands which are unlicensed according to the international convention, which gives more flexibility for the deployment of the mobile ad hoc network. However, this benefit also results in a dramatically increase in numbers of wireless equipment and systems. Accordingly, MANET has an increasingly high likelihood to suffer from the interference coming from other equipments. The diverse range of interfering applications include radio frequency identification devices; lighting;

microwave ovens; public telecommunications; other short range radio devices and low power audio, video and data links etc. Considering the coexistence of wireless PAN (see BlueTooth) and WLAN (include MANET), the potential interference must be taken into account. Some solutions and recommendation have been provided by the IEEE standard group [3], such as using Frequency-Hopping Spread Spectrum (FHSS) technology instead of Direct-Sequence Spread Spectrum (DSSS) [5], separating the ISM products apart enough from each other, and strengthening the nodes signal, etc.

- **Data Rate:** For the end-user, the most important factor is the data rate, the speed the data can be transferred between the nodes. As for the IEEE802.11a protocol and IEEE802.11b protocol based MANET, the former supports 54 Mbps, 48 Mbps, 36 Mbps, 24 Mbps, 18 Mbps, 12 Mbps and 9Mbps data rate working on about 5GHz radio frequency and the latter supports 11Mbps, 5.5Mbps, 2Mbps and 1Mbps working on 2.4GHz frequency. The data rates can be automatically scale-up (or scale-back) depend on the distance between the nodes. With the development of wireless technology, higher data rates will soon be available. Several new wireless protocols that support higher than the 54Mbit/s data rate are already proposed by IEEE Task Group, for example the IEEE802.16.1 is intended to support individual channel data rates of from 2M to 155M bit/sec [4]. With the high data rate available in the wireless environment, more and more multimedia mobile applications will be developed and the utilization of MANET could be even more popular than ever.
- **Link Range:** Link range is the maximum range that MNs can be apart and still create a connection with each other. The values in
- Table 2.2 are selected from the products specifications to show us the difference of the link range of different mobile devices in different environments. Therefore, the radio specifications of the nodes are highly environment-dependent. The negative influence on the link range is caused by the radiowave propagation, such as the reflection, diffraction, Non-Line of Sight, the Multipath propagation, etc. Normally, more obstacles such as the doors, walls can be found in indoor environments so that the performance is much worse than out-door. The values here are measured between PCMCIA card and the Access Point (AP) which is usually equipped with a

more powerful antenna. Thus, the practical results must be worse in the MANET environment where no AP exists and with low power supply. Due to all sorts of path loss [16] of radiation energy, the closer the nodes are located, the higher the data rate between them can be achieved.

TABLE 2.2 THE COMPARISON OF LINK RANGE OF DIFFERENT MOBILE DEVICES IN DIFFERENT ENVIORNMENTS

	Outdoor (m)		Indoor (m)	
	11Mbps	1Mbps	11Mbps	1Mbps
Cisco Aironet350	244	610	40	107
*Cisco AIR-CB20A	*30 (54Mbps)	*304 (6Mbps)	*18 (54Mbps)	*52 (6Mbps)
Enterasys RoamAbout	160	550	50	115
AmbiCom WL1100B	250	500	50	150
Compaq WL110	160	550	50	115

2.2.3 Energy

As we mentioned in section 2.2.1, an ad hoc node must be capable of high mobility in many applications. Therefore, most of the nodes have to be battery powered in order to keep a light weight, for instance the PDA with two AA dry cells and the lasted Nokia N95 phone with Li-on battery. Therefore, it is very important to avoid frequent replacement of the battery. Detailed power supply voltage and power consumption in different working status for some wireless PCMCIA cards is given in Table 2.3.

TABLE 2.3 THE COMPARISON OF POWER SUPPLY VOLTAGE & POWER CONSUMPTION OF POPULAR PCMCIA CARDS

	Power Supply Voltage	Power Consumption		
		Doze	Transmit	Receive
OriNOCO ComboCard	3.3VDC (+/-0.2V)	15mA	576mA	341mA
Cisco Aironet350	5VDC (+/-5%)	15mA	450mA	270mA
3Com 3CRWE62092B	3.0 – 3.6VDC			
Enterasys RoamAbout	5VDC	9mA	285mA	185mA
AmbiCom WL1100B	2.7 – 3VDC	20mA	350mA	230mA
Compaq WL110	5VDC (+/-0.2V)	9mA	285mA	185mA
LinkSys WPC11	3.3 or 5VDC	20mA	275mA	225mA
Usr 2210	5VDC (+/-5%)	(max) 600mA		

The exact amount of power consumed can be calculated depending on the numbers of bytes transmitted and intrinsic electronic consumption. To give a clear idea how the energy is consumed by the size of packets in byte, different stages of networking in MANET are studied. Most of the energy is consumed by broadcasting, self-organizing, routing (include routing recovery and data transmitting or receiving).

- **Broadcasting:** In a mobile ad hoc network, each mobile node is required to send a type of message to its neighbor nodes which are the nodes located in its communication range. This typical procedure is regarded as the Broadcasting which is an important preliminary process for many routing or self-organizing protocols. The broadcasting might occur periodically, and actively and reactively. For instance, some protocol need a neighbor table to store some data in each node, and this table can be obtained by periodically broadcasting HELLO message whose Time To Live (TTL) field is set to 1. In this case, even if there is no data traffic generated in the network, the nodes still need the energy to maintain the up-to-date information tables [10].
- **Self-Organizing:** Self-organizing is a very typical characteristic of the mobile nodes; the detailed information is given in Chapter 3. Basically, the nodes can act as an individual part, or organized into some clusters [11], or be given different hierarchies. These kinds of process can be utilized to increase the performance of overall networking. For instance, to achieve the location of each node, a certain positioning algorithm must be implemented by the mobile nodes and every node must compute its location according to the algorithm. Any calculation processed in the nodes is energy-consuming.
- **Routing:** Routing plays a very important role in MANET networking because of the changeable topology and environment. If the broadcasting method is simply used to transmit the data, every mobile node has to be involved such that the energy is consumed in forwarding the data in all the nodes. This could be a disaster for the low-energy mobile ad hoc network. However, by implementing some new routing protocol, especially those taking advantage of some extra information such as the location of mobile nodes, only part of network will participate in the routing and data transmission. Thus the overall energy could be saved and the traffic load can be reduced. Most of the routing discovery process will try to find a single route for the data transmitting. The advantage here is that this single route will possibly be the most stable or shortest link from the source to the destination so that the communication can be guaranteed. Considering the energy-consuming issue from

another point of view, the drawback is also obvious. If the source continues sending data to the destination, the energy of nodes along the same route will be consumed continuously due to the data forwarding, whereas the other nodes will be in the idle mode and just do some routine such as periodical broadcasting. The worst situation might happen when some nodes deplete their energy so that the network will break down. Several energy-aware routing protocols have been proposed to solve such kinds of problem [6], [7], [8], [9]. In light of what they proposed, the energy depletion of routing nodes could be avoided by using multi-route [12], i.e. multiple routes to the destination will be used during the transmission and the source will choose one route randomly at each time.

2.2.4 Antenna

Two types of antennas are normally installed in the mobile devices, omni-directional antenna and directional antenna.

2.2.4.1 Omni-directional Antenna

Ideally, using omni-directional antenna, every mobile node is expected to have a same size circle area around it. The radius of the circle is the transmission range of the antenna, and the node is located at the centre. Any other nodes inside the circle are detectable by the centre node. Usually more power for the antenna can achieve better end-to-end throughput and reduce the overall power consumption in the network. The reason is that the more power range the antenna has, the larger communication range can be obtained, i.e. the more one-hop neighbour every node can have. Therefore, some multi-hop routing (forwarding) will not be necessary in that situation. However, the disadvantage of increasing power range of antenna can not be ignored. With the higher power of antenna, more collision and interference may be caused and the performance will decrease dramatically. On the other hand, by reducing the power of antenna, a smaller subnet of neighbours can be detected and a small interference area can be achieved. However, there is some tradeoff here between minimizing interference range and reducing the probability of isolating subnets, reducing the multi-hop forwarding and reducing the probability of retransmission [14].

2.2.4.2 Directional Antenna

With directional antenna, two nodes can communicate with each other depending on not only the power but also the direction of their antenna. With much higher gain can be obtained from the directional antenna, more nodes in the specific direction can be able to communicate directly. With the advantage of directional antenna, some unnecessary packets forwarded into the network can be avoided. Moreover, spatial reuse of wireless channel is also possible because the MN can try to contact other nodes in other directions if the medium in one direction is busy [18].

Both the Omni and Directional mode may be supported by directional antenna. Basically, the Omni mode is used only for the carrier sensing and receiving, while the Directional mode can be used for receiving, as well as transmitting. With this antenna technology, several new Medium Access Control (MAC) protocols and routing protocols have been proposed [18] [19].

More MAC related issues are given in the section 2.2.6 in detail. The Basic Directional MAC (DMAC) protocol which is supported by the directional antenna still uses Request To Send/Clear To Send (RTS/CTS) handshake signalling method [13]. An idle MN is normally listening to the medium in Omni antenna mode. However, different from the normal MAC protocol, when receiving or transmitting the packets, both the sender and receiver will switch to directional mode with the main lobe of antenna radiation pattern pointing to the each other's direction. The Network Allocation Vector (NAV) is used in IEEE802.11 MAC to indicate the duration for which the MN must defer transmission to avoid the interference with other ongoing transmission in neighborhood. In DMAC, the NAV must be directional as well (so called DNAV). In other words, the NAV is related to a certain direction in DMAC. An updated DNAV table is stored in the MN to indicate the duration needed to defer transmission for each direction. Figure 2.1 illustrated a simple case with DMAC protocol.

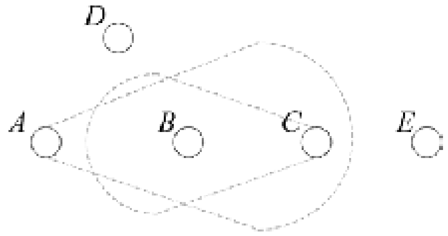


FIGURE 2.1 ILLUSTRATION OF THE DMAC PROTOCOL WITH A SIMPLE NETWORK TOPOLOGY

There is a communication between nodes *A* and *C*. Both *A* and *C* set their antenna direction towards each other. The RTS from node *A* or CTS from node *C* can be heard by *B* and the DNAV table is updated. If the node *B* attempts to initiate a transmission to node *E*, it must first check the DNAV table to obtain the medium status. With the aid of DNAV, node *B* notices that the transmission towards node *E* must be postponed due to other communication at the same direction. But the communication with node *D* is likely to be safe for node *B* after the DNAV check. Therefore, the channel is being reused spatially.

The implementation of the directional antenna can enhance the network performance in MAC level as well as the routing level, but unfortunately it is not a technology we can rely on. The following situation is actually very common in wireless environment [20]:

- **Hidden Nodes:** There is no doubt that the directional transmission range can be enhanced by using directional antenna and the interference area can be significantly reduced. The power in other directions is weaken to a very limited level, which may cause some Hidden Nodes in those areas. Assuming that in Figure 2.1, there is a communication between nodes *D* and *B*, and *B* is not in the communication range of node *E*. If the node *E* wants to send messages to node *C*, then node *C* will respond with a CTS to *E* with the directional mode pointing to *E*. Since node *B* is working on Directional mode, it may not hear the RTS from *E* or the CTS from *C*. The incorrect DNAT table in B will tell it that it is safe for the transmission in the direction of E, which causes interference. However, this effect can be avoided by using Omni-directional antenna, since *C* can be prevented from communication after it gets the RTS from *B* on Omni mode.
- **Deafness:** Deafness is a conspicuous problem caused by the directional antenna. A MN uses a directional antenna beamforms towards the intended destination. As a

result, it will look deaf for the transmission from the other directions. In Figure 2.1, if node *B* is communicating with the node *E*, the transmission from *D* to *B* can not be heard by *B*. Likewise, the Deafness is avoidable by using Omni mode since all other neighbours must be set to idle.

2.2.5 Mobility

MANET is very flexible due to the varying mobility of MNs in all sorts of environment. Theoretically, many observable factors could be regarded as a component of Mobility. According to the study to date, these parameters can be put into two categories: Environment factors and Movement factors.

The environment factors include the number of the nodes (*N*), available free movement area (*S*), antenna RX range (*R*), and nodes distribution or probability (*D*). However in terms of the characteristics of different environment, the movement characters could be very distinct from each other. For instance, given three different environments, Road Traffic, Indoor Meeting and outdoor Park, the difference of the mobility is significant. Assuming that every person and vehicle is equipped with a wireless product, the difference in mobility will be obvious. For example, on the road, the speed of a moving vehicle and a walking person has about 10-100 times difference. As for the directions, the mobile vehicle nodes must follow the road whereas a person can towards any direction when crosses the road. When a mobile ad hoc network is designed for an indoor environment, for instance, for a conference, the network could be almost static and the available space is also very limited inside a room. Another example is an outdoor park environment where people normally enjoy the freedom. They may stay somewhere chatting or run and walk. The directions in this case are relatively uncertain. Therefore, the movement factor must be considered very carefully to reflect the real world. Generally to say, the MN can move individually (the Park case) or form groups towards one position with slightly different individual mobility (the Road Traffic case).

In order to thoroughly analyse the performance of a new protocol in a mobile ad hoc network, it is very important to accurately describe the movement as well as the real-world varying environment. Two types of synthetic mobility models are proposed, Entity Mobility and Group Mobility. The Entity Mobility model attempts to mimic the movement of the individual mobile node. For each MN, change of speed and direction or stopping may happen at some time tick or during some time slots due to the possible restraints from the real environment, for example, cars can not turn around when running in the highway; people can not walk through the room during the meeting, etc. Six different but typical Entity Mobility models are listed here:

Random Walk Mobility Model: It is a simple mobility model in which all the MNs can randomly change speed and direction [21].

Random Waypoint Mobility Model: This model inserts pauses time between the changes of speed or direction. In this model based scenario, the MN will stay in a position for a certain period of time then choose a random speed and direction and continue moving. The speed is chosen randomly from a fixed range [22].

Random Direction Mobility Model: A significant weakness of the previous model is the coverage of mobility. In most cases, the movement will just occur in the neighbourhood area (density area) of the start position. Thus some parts of the predefined area become blind areas because they are away from the start position. In the Random Direction Mobility Model, all MNs will be forced to move toward to the side of predefined area [54].

Boundless Simulation Area Mobility Model: This model converts a 2D rectangular area into a torus-shaped area. In other words, unlike other models in which the MNs must reflect off or stop when they arrive at the side of the area, the MNs in this model, they will continue the movement into the area from the other opposite side. A relationship exists between the current velocity and direction and previous ones. A velocity vector $\bar{v} = (v, \theta)$ is used to represent the MN's velocity v and direction θ; the MN's position is represented as (x, y). Both the velocity and direction will be updated at every Δt time according to the following equations:

$$\begin{aligned} v(t+\Delta t) &= \min[\max(v(t)+\Delta v, 0), V_{\max}] \\ \theta(t+\Delta t) &= \theta(t)+\Delta\theta \\ x(t+\Delta t) &= x(t)+v(t)*\cos\theta(t) \\ y(t+\Delta t) &= y(t)+v(t)*\sin\theta(t) \end{aligned} \tag{2.1}$$

where $V_{\max}$ is the maximum velocity; Δv is the change in velocity which is uniformly distributed between $[-A_{max} * \Delta t, A_{max} * \Delta t]$, A_{max} is the maximum acceleration of the MN; $\Delta\theta$ is the change in direction which is uniformly distributed between $[-\alpha * \Delta t, \alpha * \Delta t]$, and α is the maximum angular change in direction [57].

Gauss-Markov Mobility Model: In order to eliminate the sudden stops and sharp turns possibly encountered in other models and adapt to different level of randomness, the MN's velocity and direction can be changed by tuning a parameter $\alpha (0 < \alpha < 1)$. The new speed s_n and direction d_n will be calculated by the following equations:

$$\begin{aligned} s_n &= \alpha s_{n-1} - (1-\alpha)\bar{s} - \sqrt{(1-\alpha^2)}\, s_{x_{n-1}} \\ d_n &= \alpha d_{n-1} - (1-\alpha)\bar{d} + \sqrt{(1-\alpha^2)}\, d_{x_{n-1}} \end{aligned} \tag{2.2}$$

where $\bar{s}$ and $\bar{d}$ are the mean value of speed and direction. $s_{x_{n-1}}$ and $d_{x_{n-1}}$ are random variable from a Gaussian distribution [55].

Probabilistic Version of Random Walk Mobility Model: A probability matrix is used in this model to determine which direction the MN should move. This mobility model can be used in some cases where the MNs move towards certain direction with higher probability instead of random chosen directions [35].

The aforementioned six models are used to mimic the movement of MNs which are independent of each other. However, in some situations, the group phenomenon can not be disregarded when we study ad hoc mobile nodes. For example, in a workshop, some workers can be assigned to work together to carry goods led by a manager, but there could be another group which is working on a product line and stay static. In order to mimic thus situations, several Group Mobility models have been proposed. The most general one discussed in MANET research, Reference Point Group Mobility (RPGM) model [59] is described below.

The RPGM model mimics the random movement of the groups and the MNs inside each group in MANET. A so called logical center of the group is used to represent the motions of the group by a vector $\vec{GM}$. All the motion of MNs is characterized by this vector. Each MN should move randomly around a pre-defined reference point whose movement is dependent on the movement of the logical center. Therefore, the new position of the MN is determined by the combinational effect of random self-movement

$\dot{RM}$ and its motion vector of the reference point, $\dot{RP}$.

The performance of MANET protocols can vary significantly with different mobility models of MNs and with the same mobility but with different parameters. A thorough discussion on the mobility models can be found in Chapter 4.

2.2.6 Protocols-related Issues

In this section, the protocols-related issues of mobile nodes are discussed.

2.2.6.1 Wireless Medium Issues

The properties of the wireless medium make the design of the MAC protocol much more challenging than the wired network. As the entities of the communications, MNs have to deal with various serious channel issues by using MAC methods.

a). Radiowave Propagation

The propagated signal in the MANET can undergo three primary physical modes [15]:

Reflection: Upon arrival at a surface, the propagated signal will be absorbed, reflected or a combination of both. The reflection depends on the physical properties of the surface, such as material, texture, and the properties of the signal like wavelength, incident angle, etc.

Diffraction: This occurs when obstacles are impenetrable by the radio wave. An example is a diffracted wave front can be formed when the signal is obstructed by sharp edges in the propagation path. In the MANET environment, these sorts of obstacle with sharp edges can be found easily. The resultant diffracted signal depends on the geometry of the edges and the properties of the incoming signal.

Scattering: When there are many small objects relative to the wavelength of the signal in the propagation path, the signal will be broken into many directions. The resultant scattered signals will have either a constructive or destructive effect on the original signal.

Because of the pre-mentioned three primary propagation mechanisms, Path Loss [16] will occur during the propagation from the transmitting antenna to the receiving antenna.

The Free Space Path Loss (FSPL) [17] is a fundamental analysis method of the path loss. According to its definition, the signal decays with the power of distance and depends on the wavelength of the signal.

$$FSPL \quad (4\pi d / \lambda)^2 \tag{2.3}$$

Line of Sight Path Loss is given by

$$PL_{LOS} = FSPL \quad 10 \cdot n_1 \cdot \log(d) \tag{2.4}$$

which is the addition of FSPL and the loss caused by the propagation environment. Parameter n_1 is a scaling correction factor which depends on the attenuation of the propagation environment. Obstructed Path Loss occurs due to the attenuation when the signal is transmitting through the obstacles. It is normally hard to predict and its measure usually relies on some empirical means. The Multipath and Fading issues should not be avoided because of the reflection, diffraction and scattering of signal. The receiving signal at the receiver is actually a superposition of the signals from different propagation paths. The result is that the receiving signal is variable in amplitude with time. The Fading is a variation of signal power at receivers, caused by the node mobility that creates varying path conditions from the transmitter.

As a result of the signal propagation properties, only the MNs within a specific radius range to the source MN can capture the signal from it. They are so called one-hop neighbours of the source. Accordingly, two special types of mobile nodes may exist in MANET.

Hidden Nodes**:** If two nodes are far apart (out of antenna radio range) or there is some barriers between them, they can not detect the traffic status of each other [20] [23]. This is so called *Hidden Nodes* problem which may cause a high possibility of collision. Figure 2.2(a) simply illustrates this problem. If node *A* can not hear the transmission or receive from node *B* but it wants to communicate with *B*, node *A* will send the packets which will be forwarded to the destination *B*. Unfortunately node *B* is receiving data from other nodes, say node *C* when packets from A arrive. Thus a collision will happen.

Exposed Nodes**:** Multiple Access with Collision Avoidance (MACA) [26] mechanism may decrease the Hidden Nodes problem, but it will also cause another possible problem called *Exposed Nodes* [23]. Give source node *A* and destination node *B* in

Figure 2.2(b), node *A* can not detect any traffic related to *B* and sends RTS packets, then waits for the CTS. If node *B* is inside an interference range of other nodes, say node *D*, it might not get the RTS message correctly or the CTS sent out by him may not arrive at *A* correctly because of interference. If this situation continues for a long time, node *A* will think the link to *B* has lost but it is not true. The worst case is node *B* even can not send out RTS message when it wants to communicate with others because of heavy traffic around itself.

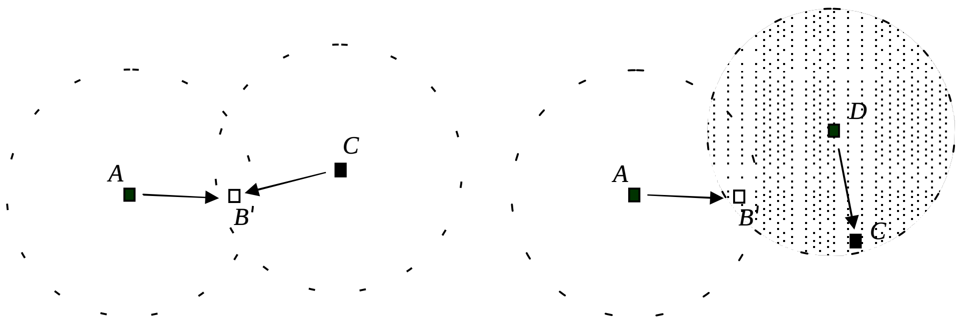


FIGURE 2.2 AN ILLUSTRATION OF HIDDEN NODES & EXPOSED NODES ISSUES

b). Half-Duplex Operation

It is very difficult for the mobile nodes to receive data whilst sending messages as the signal energy sent by it could partially leak into the receive path. Due to this so called *self-interference* [28], the received signal which has less power than the leakage energy can not be detected by the nodes. Therefore, normally the mobile nodes can not work in Full-Duplex mode using Ethernet MAC protocols. Instead, Time Division Duplex (TDD) and Frequency Division Duplex (FDD) [101] with collision avoidance methods must be implemented in both up-link and down-link in MANET.

c). Channel Error

Due to propagation issues, transmission performance in wireless networks could be much worse than that of a wired network. As a result of the Fading and Multipath influence on the signals, wireless channels could have a 10^{-3} Bit Error Rate (BER) compared with 10^{-6} BER in wired systems [28]. To minimize this damage, an ACK mechanism is used in link layer and in both link and transport layer. The MNs will trigger a timer when finishes sending data then wait for the ACK message from the destination. If no ACK is received before timeout, the data will be retransmitted.

d). MANET MAC Protocol

The wireless network can be classified into two categories: Distributed Wireless Networks, i.e. mobile ad hoc networks discussed here and Centralized Wireless Networks which is running as an extension of wired networks using wireless-wired bridge (Access Point). Unlike mobile ad hoc networks, the Access Point functions as a base-station to control all the connections. Based on this knowledge, wireless MAC protocols can be classified into two categories as well: Distributed MAC protocols and Centralized MAC protocols [28]. Figure 2.3 shows the classification of wireless MAC protocols. The Centralized MAC protocols are not considered in this study.

In MANET, if there is just one MN sending the data, the transmission will be successful. But if more than one MN are transmitting messages in the same time, a collision will occur; therefore the MNs need to contend for access of the shared medium. Random access to the medium is a good solution for this problem. ALOHA [29] [30] was the first important protocols proposed for random access. However, as mentioned in the sub-section Half-Duplex Operation, ALOHA is not ideal since it is difficult to detect a collision in the channel when the mobile node is sending data. Instead, collision avoidance carrier sensing method is implemented in MANET to minimize the possibility of collision.

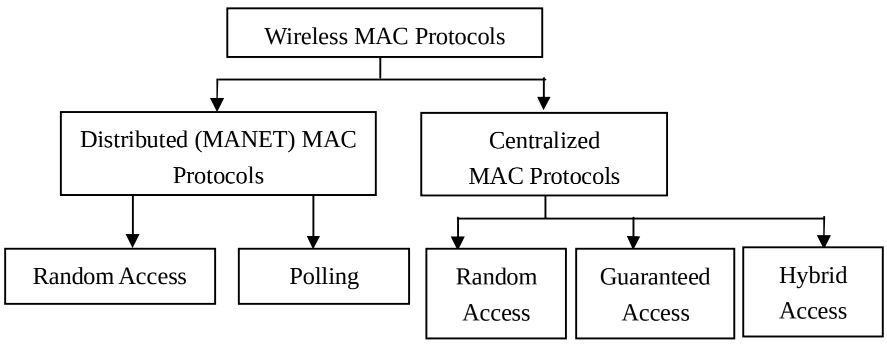


FIGURE 2.3 THE CLASSIFICATION OF WIRELESS MAC PROTOCOLS

Two typical collision avoidance mechanisms have been proposed:

Collision Avoidance with Out-of-Band Signaling Busy Tone Multiple Access (BTMA) [24] is an example of such method. Any nodes hearing the transmission will broadcast a busy tone and any nodes hearing this busy tone will be prevented from transmission. By this method, the hidden nodes can be reduced. Recalled the Hidden Node example in Figure 4(a), node *B* can hear the transmission from node *C*, then a busy tone is sent by it to its neighbor. Node *A* gets this busy tone and postpones its transmission to *B*. All the nodes in 2***R*** (***R*** = antenna communication range) range of the source node have to be quiet during the transmission of A, which definitely decreases the efficiency and increase the number of Exposed Nodes. As a variance of the BTMA, the Receiver Initiated-BTMA (RI-BTMA) [25] where the busy tone is sent out by the destination gives a better solution for the Exposed Node but ignores Hidden Nodes.

Collision Avoidance with Control Handshaking Multiple Access with Collision Avoidance (MACA) [26] is a precedential protocol of IEEE802.11 MAC protocol (CSMA/CA) using the handshaking to avoid the Hiding Nodes issue. Basically, Node *A* broadcasts a Request To Send (RTS) message before it sends out the data packets. The intended destination will be requested to reply a Clear To Send (CTS). Any nodes that can receive either RTS or CTS will not generate any data traffic during the transmission from node *A*. By this method, the Hidden Nodes will be reduced significantly but in the meanwhile we sacrifice the bandwidth due to the overheads caused by the handshake.
As a derivative of MACA, CSMA/CA MAC protocol, so called Distributed Foundation Wireless Medium Access Control (DFWMAC) [27] implemented in IEEE802.11 wireless network provides three types of handshaking messages with interval periods. When a MN needs to transmit data, it waits for not less than one Distributed Inter-Frame Space (DIFS) period of time until the channel is idle. A RTS packet is sent out to announce the requirement of the channel. The destination MN should responds with a CTS packet to indicate it is ready to receive. The sender sends the data if the channel is free for Short Inter-Frame Space (SIFS) period. If the data reaches destination without errors, an ACK packet has to be sent to the source in SIFS channel-free period later upon finishing the data receiving. Figure 2.4 illustrates this mechanism. If the MN which has sent RTS or DATA does not receive CTS or ACK before timeout, it will initiate a back-off process. The MN first generates the back-off

time as a number of time slots uniformly distributed in [0, *CW*], where *CW* is the current contention window parameter. The MN monitors the channel for more than DIFS and decides if the medium is free or not. Only if the channel is free does the MN count down the back-off time. If the channel is busy again, it stops counting. This process continues until the back-off time goes to zero. Then the MN can re-transmit the next frame at once without waiting for DIFS. Any node hearing the RTS or CTS packet must stay idle for a period of time to save energy. This time duration can be captured from those packets which contain a field called Network Allocation Vector (NAV). With awareness of medium state, the idle nodes count down NAV to zero before sensing the channel again.

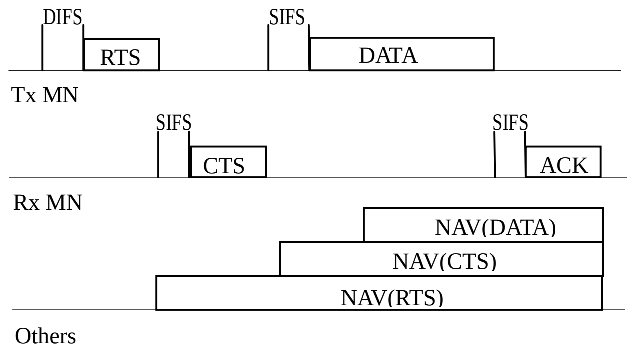


FIGURE 2.4 ILLUSTRATION OF THE HANDSHAKING MAC MECHANISM

The following approaches have also been proposed for improving the MAC protocols. [31] has a review of these approaches in more detail.

- **Using Adaptive Transmission Range/Power Control:** Longer transmission range could increase the numbers of one-hop neighbors as mentioned in *Energy section*,. In the MAC level, this means the reduction of link failure caused by the intermediate MNs. The weakness of this approach is that it increases the Exposed Nodes due to a larger neighborhood.
- **Using directional/Adaptive Antenna**: The problems caused by the Hiding Nodes can be solved to some extends by using directional antenna instead of omnidirectional antenna for MN. This has been discussed in *Antenna section*.
- **Fairness-Based Approaches:** The fair wireless MAC protocol is proposed to

ensure fair competition among the MNs or flows under the time and location dependent wireless channel errors.

- **Energy-Efficiency-Based Approaches**: Inefficient use of the energy of MNs can not only lead to more link failure, but reduce the life of MNs. Idle mode of a MN is the most popular idea implemented in many protocols. For instance, when the MNs hear the busy tone they will configure themselves to be idle for a specified time. In the HIgh PERformance LAN (HIPERLAN) MAC protocol [32], the MN should designate a power-supporter node before it goes idle. All the data goes to this node will be buffered in its power-supporter during its hibernation.

Besides the Random Access protocols, another type of particular MAC protocols for MANET is also important. It is so called Polling protocols [33] [34]. Similar to Polling Ethernet networks, a token is distributed. Only the MN possessing the token has the privilege to transmit data. However, Polling protocols are not prevalent in MANET systems. This is due to the high flexibility of mobile ad hoc network, as frequent token exchange will cause many problems. For instance, Token loss will cause the entire network to breakdown.

2.2.6.2 Routing

Due to the frequently changing topology of a MANET, the routing protocol used by the MNs has a significant effect on the overall performance of the network. The routing protocols for a MANET can be either *proactive* or *reactiv*e (see Figure 2.5) depending on MN's reaction to a topology change. A MN running a proactive routing protocol will broadcast a routing-related message to its neighbor when it detects a change and the neighbors will use it to update their own routing table then broadcast more routing-related messages to others. This process occurs in each MN and finally all the MNs will keep a routing table to all the possible destinations. Typical proactive protocols proposed include: Destination Sequenced Distance Vector (DSDV) [65], the Wireless Routing Protocol (WRP) [36] and Routing Information Protocol (RIP) [37]. Proactive protocols are less intelligent and efficient than the reactive ones. Even if the MNs do not need the routing information, the routing-related messages must be sent through the network. Therefore, the traffic caused by the routing messages will scales heavily with increasing size of the network. The bandwidth is wasted by unnecessarily initiated routing information.

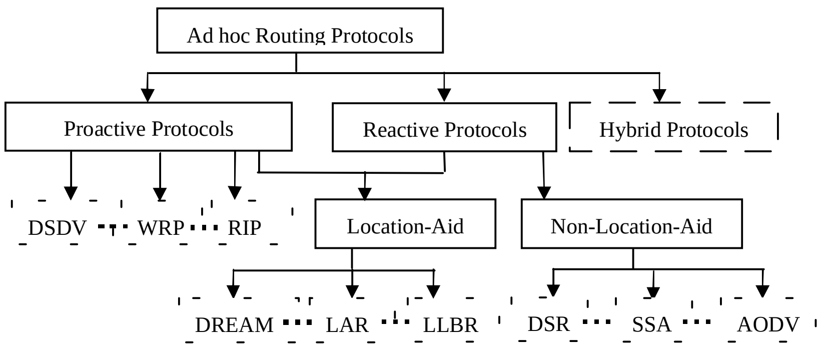


FIGURE 2.5 THE CLASSIFICATION OF ROUTING PROTOCOLS IN MANET

Unlike the proactive protocols, reactive protocols only exchange routing information when the source node needs it. Dynamic Source Routing (DSR) [66], Signal Stability-based Adaptive Routing (SSA) [38], and Ad Hoc On Demand Distance Vector Routing (AODV) [1] are typical reactive protocols. Routing in reactive protocols typically consists of three stages: Route Discovery, Data Transmission and Route Maintenance.

- **Route Discovery:** deals with how to request routes to the destination and how to respond the request to the source.
- **Data Transmission:** deals with how to transmit the data from the source to the destination. For instance, it decides on the format of the packet and the routing table. The data packet forwarded in DSR should include the full route to the destination, but the AODV data packet just needs the next-hop address included.
- **Route Maintenance:** solves the route breakage issues and keeps the routing table up to date.

The AODV is used as an example to describe the three stages in more detail. When a MN desires to send a message to a certain destination and does not have a valid route to it, it initiates a Route Request message (RREQ) to its neighbors. The neighbors capture the message and forward it to their neighbors, and so on, until either the destination or an intermediate node with fresh route information to the destination is found. In order to justify if the routes stored in MNs are fresh enough for the request or not, a destination sequence number is included in the RREQ and each MN should maintain a own sequence number as well. Only the nodes that have a larger sequence number than the RREQ received can reply to the request. During route recovery, the intermediate MNs will record the address of the neighbor from which the first copy of RREQ comes into its routing table which can be used for the reverse path. The destination or the node with a fresh enough route to the destination respond with a Route Reply message (RREP) back to the source along the reverse path. MNs along this path set up forward route entries in their route tables which point to the node from which the RREP came. These route entries will be used for the data transmission. For the route maintenance, if the moving node is the source it can initiate another round of RREQ recovery. If the intermediate node moves, it will propagate a link failure notification to its upstream neighbor to indicate the route damage, and so on until the source gets the notification. A periodically broadcasted HELLO message can be used in AODV to sense the one-hop neighbors and keep track of local connections.

With the aid of location information of MNs, several protocols have been proposed as the variants of the reactive routing protocols. Unlike the non-location-aid protocols which may force all the nodes be involved in the messages forwarding, MNs use locally stored location table which contains location information of other nodes to direct the message to the destination. In that case, only those MNs in a specific area which normally locates in the same direction with the destination) can forward the messages. Thus, the overall overhead caused by the routing algorithm can be reduced to some extent, the energy of MNs outside the forwarding area can be saved, and the traffic load due to the message flooding can be lessened. The popular protocols using location information include the Location-Aid Routing protocol (LAR) [73], Distance Routing Effect Algorithm for Mobility (DREAM) [68].

- **Location-Aided Routing (LAR)** algorithm was introduced in [73]. LAR actually does not define a location-based routing protocol. Instead, it proposes a way of using the position information to enhance the route discovery phase of the reactive ad-hoc routing approaches. Using the assumption that nodes have information about other nodes' positions, LAR uses the location information to restrict the flooding area instead of flooding the packets to the entire network. Two schemes are proposed in LAR. The first scheme uses a rectangular request zone which is defined as the smallest rectangle that includes the current location of the source node and the expected zone. When a node receives a route request, it discards the request if the node is not within the rectangle specified by the locations of four corners included in the route request. In the second scheme, it assumes that source node knows the location of the destination node prior to the moment at which route discovery is initiated; the distance between the source and the destination is calculated and included into the route request message, along with the coordinates of the destination.

- **Distance Routing Effect Algorithm for Mobility (DREAM)** algorithm introduces two concepts, distance effect and mobility rate. In DREAM, each node maintains a position database that stores the position information about other nodes in the network. An entry in this position database includes a node identifier, the direction, the distance to the node, and the time when this information was generated. Each node regularly floods packets to update the position information maintained by the other nodes.

The location information can be achieved directly from the GPS signal or by self-positioning of nodes. The latter method bring more challenges to the Discovery and Maintenance in routing, Topology Discovery and Location Information Maintenance. Topology Discovery describes how to generate the network geographic topology. A typical discovery method is *Euclidean Propagation* [39] where the location is calculated according to triangular rules. As a very important parameter, the distance between the neighbours can be obtained by measurement of receiving signal's power, by estimation based on amount of hops to Landmark node, by Time of Arrival (ToA), or Time Difference of Arrival (TDoA) [40], etc. After the discovery, a location table is stored in every MN for the routing. Due to the movement of MNs, the locations must be kept up-to-date as much as possible, otherwise the stale location used by the routing may direct the messages to a wrong way. The Location Information Maintenance algorithm shouldn't cause too much overhead and must work consistently with routing methods.

2.2.6.3 Clustering and Hierarchically Structuring

As mentioned before, due to the infrastructure-free characteristics every mobile node in MANET can act as a normal information source and destination or router. In this mode, each node will play a very similar role in the routing, forwarding, etc. With the number of mobile nodes increase, the topology is getting extremely complicated. More self-organizing messages needed to be exchanged in the network so that the traffic load will be a big issue which will deteriorate the overall performance and efficiency.

Some interesting ideas have been proposed to solve this problem, using so called Clustering and Hierarchically Structuring [41][42]. The entire network is clustered into a number of partitions. A cluster-head is chosen inside each cluster. Therefore, most of the detailed information can be only exchanged within the cluster and the cluster-head is responsible for the aggregated information exchanged amongst the clusters. In this mode, the cluster-head mobile node will have to perform a much heavier self-organizing job, such as route recovery, messages forwarding than others. A typical example of this type of protocol is Cluster-Based Routing protocol (CBRP) proposed in [43]. When a cluster is formed, the node can work on three modes: cluster-head, member or undecided. Depending on the cluster formation algorithm (i.e. Min-ID) a node can be selected as the cluster-head and the rest of the nodes in this cluster remain members or undecided. The protocol relies only on local information; the nodes exchange HELLO messages from time to time in order to keep track of the network topology around them. This message contains the neighbour node and link status (uni-directional or bi-directional) information, and the nodes receiving the message update their Neighbour Tables. The route discovery process starts by flooding the network, but only the cluster-heads are flooded as they are the entities keeping information about their members, with Route Request packets for a specific destination node. When the destination receives this packet, it replies back along the reverse path with a Route Reply packet. The complete path is contained in the reply message, and the source node now uses source routing to forward the packets. If a link along the route is broken, the previous node that realises that the link does not exist informs the source node about it with a Route Error packet. Then, using the Local Route Repair mechanism, this node uses the information stored in its routing tables and forwards the packet along a different route, changing the route header of the packet. Upon receiving this packet, the destination node replies back to the source node with the modified route information. By this method, the overall route discovery overhead is reduced and flooding is controlled locally.

These clusters can be hierarchically structured. The basic idea is that the addresses of the mobile nodes are assigned hierarchically and aggregated information is exchanged according to the levels of hierarchies.

2.2.6.4 Quality of Service

Multimedia and real-time communications have become the most important applications we should rely on. Therefore, the Quality of Service (QoS) [44] [46] requirement, such as bandwidth reservation, loss, delay, jitter etc must be met. Unfortunately, the retransmission mechanism of MAC protocols mentioned before is not suitable for real-time streaming and it is also difficult to obtain the QoS due to the lack of centralized control in MANET. Two methods can be implemented by the MN:

- **Priority Buffer** Normally, the MN has just one single queue for the outbound packets, and the First In and First Out (FIFO) mechanism is adopted. To guarantee some frames like real-time data can be transferred earlier than others, Priority Scheduling (PS) is needed to be implemented in each node [45]. The PS marks each frame with different priority. The low priority frame can only be transmitted when no higher priority frames exist in the queue. Alternatively, a smaller probability of transmission is allocated to the low priority frames and larger probability to the higher priority frames.
- **Differentiated QoS** Using the differentiated QoS method [46], each flow can be assigned a certain level of QoS. Basically, in order to achieve the differentiated QoS, the MAC protocol must provide the ability of adjusting the back-off time or persistence parameters. The smaller back-off time and Inter-Frame Space (IFS) is

needed to be able to send the real-time flow before the non-real-time flow. Additionally, more QoS information must be stored in each MN. For instance, in Dynamic Bandwidth Allocation/Sharing/Extension (DBASE) approach, a ReSerVation Table (RSVT) is stored in each MN. The RSVT contains access sequence, MAC address, service type and required bandwidth for the reservation.

2.2.7 Security

Wireless networks introduce many new security challenges over traditional wired networks. Being within the transmission range of a sender, a malicious user can easily intercept his packets without any physical access to the network. Further, the notion of a mobile ad hoc network also introduces some new security vulnerabilities because the ad hoc nodes can work as a router for the data forwarding and there is no infrastructure such as an authentication server, or a Virtual Private Network (VPN) server in the network. The security issue of the ad hoc nodes can be classified into two levels.

- **User Level Security** Considering the previously mentioned properties of the ad hoc nodes like physical and mobility properties and major working environment like public place, the likelihood of being lost or stolen may be much higher than the terminals in wired network. Accordingly, anybody can easily access the network though the nodes if there no any protection has been done on them. Similar with the Personal Identification Number (PIN) used by the mobile phone, the ad hoc nodes must provide the first level security measure to prevent unauthorized users.
- **Network Level Security** This level of security is to prevent malicious users joining the mobile ad hoc network using unauthorized nodes. Obviously, the messages transferred in the network can be encrypted by strong enough algorithms, which can reduce the possibility of eavesdropping. However, this could cause an embarrassing situation when the authorized user wants to join the network but has no idea about the key which should be configured in the nodes. Many-to-Many Invocation (M2MI) [47] gives us a compromise solution. Basically, in order to establish a secure communication channel, each node must possess a group authentication key which is established and maintained by connecting an authorized node through a secure communication channel, e.g. PDA cradle, IrDA, etc. Only

the node which has the group key can be regard as a potential legal user. The group key will be used for establishing session keys that will be used to secure all the communications.

2.2.8 Fashion

Fashion is a more of a commercial aspect than a technical-related issue, but it is definitely one of the key properties which can decide on the level of the popularity of a MANET. The history of the mobile phone can be thought of as a reflection of the evolution of the ad hoc nodes. Most of mobile phone end users have little interests in new developing communication technology and all they care about is the look-and-feel of the mobile phone. Tens of mobile phones with new designs rush into the market every month. With personalized covers, modern profile, full-color screen, etc, the mobile phone became an element of fashion. Most likely, the mobile ad hoc network will become the forth generation of wireless communication system, but it may only take off if it becomes fashionable to use an ad hoc node. Some latest mobile phones are Wi-Fi enabled, so the fashion property can for sure boost the wireless ad hoc market, and it can be foreseen that the wireless enabled gadgets will become an important part of our modern life, which implies that the researchers have to address on more particular wireless environment.

2.3 INTRODUCTION TO THE SIMULATION OF MOBILE NODES

It is not necessary to construct a real MANET with many mobile nodes. Usually simulators are used to simulate the mobile ad hoc network environment and scenarios. A number of network simulators have been designed. OPNET [37] and Network Simulator 2 (ns2) [51] are probably the most popular ones. The former is a commercial product, but the latter is an open-source project and widely used by the researchers. Theoretically, these simulators can simulate most of the properties of the mobile node except the physical and environmental specification part discussed in section 2.2.1.

Network Simulator 2 (ns2) is a discrete event simulator targeted at networking research. ns2 provides substantial support for simulation of Transmission Control Protocol (TCP), routing, and multicast protocols over wired and wireless (with CMU Monarch extension [96]) networks. In ns2, the IEEE802.11b protocol is implemented for every ad hoc mobile node. To simulate the mobile ad hoc network, there are four main steps that must be done to the mobile nodes, antenna configuration, agent configuration, mobility configuration, and traffic configuration. Each node has an omni-directional antenna. Some parameters of the antenna are supported for the configuration, such as antenna position on the node, transmitted signal power, gain of transmission and receiving, and frequency, etc. The receiving signal power can be computed by some radio propagation models like Free space model [50]. Thus we can get different signal range of antenna by configuring these parameters, say $d \quad \sqrt{\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 P_r L}}$ in Free Space propagation model. Every mobile node can be attached an agent to handle different kinds of self-organizing information, for instance a Routing agent, a Positioning agent, a Clustering agent etc. For the mobility configuration, the space range of movement, the velocity of node, the number of node, and the duration in a position can all be set. In ns2, the moving directions of nodes are randomly chosen and the nodes can move to any position in the specified range. Once these configurations and the traffic sources and destinations are set up, it is possible to run the network with the help of an embedded Time Scheduler [51].

2.4 CONCLUSIONS

The research on the MANET is actually a massive framework which crosses many aspects in the field of wireless communications. The properties of the ad hoc node are discovered and described, although it is sometime not easy to study the mobile nodes without the knowledge of the entire network. This chapter discussed many properties of mobile nodes and relevant network issues. Based on this very broad study from the mobile node’s point of view, it can be concluded that:

- The mobile node is physically small and light which makes it capable of high mobility and of working in many environments;
- The mobile node currently works using ISM frequency but should support new signal operation technology to prevent interference from other systems;
- The mobile node is required to support high data rates to provide the end-user with multimedia or real-time services;
- The mobile nodes are normally powered by the batteries with limited energy,

therefore adopting some energy-awareness broadcasting, routing, self-organizing protocols becomes very essential;

- Mobility characteristics have to be carefully considered before MNs are deployed into a specific environment;
- Better network performance can be achieved using the equipment such as intelligent antennas which can work on both Omni and Directional mode to reduce the negative effects of Hidden Nodes, Exposed Nodes, etc;
- A mobile node has the capacity of self-organisation, e.g. self-positioning, clustering, which significantly differentiate MANET from other infrastructure-based networks;
- Both user level protection and network level security protection are required to keep the mobile node safe during communication;
- The fashion of the mobile node (wireless gadget) is a key factor to boost the wireless networks, which will bring more challenge to the MANET researchers.
- The simulation tools must incorporate more properties of a MN provide more reasonable and realistic simulations.

With the analysis of mobile nodes, a better understanding of MANET in both reality and research context is achieved. The self-organisation of mobile nodes along with the routing, mobility models in MANET, network simulation and emulation are further studied in the rest of this thesis.

Chapter 3: SELF-POSITIONING AND LOCATION BASED ROUTING PROTOCOL

3.1 INTRODUCTION

Mobile Ad Hoc NETworks (MANET) consists of wireless mobile hosts which can communicate with each other in the absence of a fixed infrastructure. The mobility of Mobile Nodes (MN) affect the network topology and consequently result in frequent updates of the routing tables. Additionally, the limited bandwidth compared to wired networks is another key factor that needs to be considered when investigating packet routing algorithms. Researchers have proposed several approaches, such as the Ad hoc On Demand Distance Vector routing (AODV) [1], the Dynamic Source Routing (DSR) [66] etc, to solve the routing related issues. Unlike these conventional popular protocols, the Location-Aid Routing (LAR) [73] algorithm and Distance Routing Effect Algorithm for Mobility (DREAM) [68] differ in that they can take advantage of the location information of each node in order to reduce the routing area and route discovery overheads. Both of these protocols assume all the nodes can receive the Global Positioning System (GPS) signal, with which their position is detected. However it is not always possible as GPS does not work indoors. MANET is capable of being constructed anytime and anywhere, and therefore a more flexible and powerful approach needs to be considered. An improved algorithm is necessary that uses location information for its optimisation regardless of the presence of GPS signal. Moreover, such information can be used for location based applications, such as location maps, local news, traffic information, etc. This chapter defines a new algorithm for the positioning of MNs, which can operate in both GPS-free and GPS-aided environments. GPS coordinates can be calculated if two or more neighbouring nodes have GPS based coordinates, otherwise a relative local location is provided instead, which is sufficient for the routing algorithms. A novel location based protocol that integrates the self-positioning algorithm as the location discovery solution is also proposed in this chapter.

3.2 MOBILE NODE POSITIONING IN MANET

3.2.1 Related Works

The main aim of the positioning algorithm is to optimise the routing algorithms based on the node's position and to reduce the traffic load. However, most of the work depends on GPS to get the position, and they are not normally operational due to some political issues and the technical limitation of GPS. Several papers propose a number of theoretical methods of positioning without GPS in MANET.

Ad Hoc Positioning System (APS) was proposed in [39] as an extension of both distance vector routing and GPS positioning to improve the work especially for the network with a limited fraction of nodes that have self location ability. As a distributed, hop by hop positioning algorithm, APS gives us three propagation algorithms, "DV-Hop" propagation, "DV-distance" propagation, and "Euclidean" propagation. By employing landmarks, the distances to the landmarks are presented in hop and distance for DV-Hop and DV-distance which is measured using radio signal strength respectively. The third method works by propagating the true Euclidean distance to the landmarks, therefore the location-unknown MN must have at least two neighbours which have location estimation relative to the landmark. The "Euclidean" method proved that it can provide a more accurate estimation at the cost of more communication.

Another Euclidean-distance based, but distributed and infrastructure-free positioning algorithm without the aid of GPS is presented in [52]. According to this algorithm, every MN should broadcast the distances between the neighbours and itself so that every node knows one or two hops neighbours' distance in his local area. The Local Coordinate System (LCS) is defined by the centre node itself by choosing its two neighbours. Every node can get its own Local Coordinate System. To adjust all the individual LCS to the same direction, the algorithm requires a third node which belongs to two different local groups to get rid of the deviation of direction. Afterwards, the MNs then recalculate their locations in the Network Coordinate System.

Triangulation via Extended Range and Redundant Associated of Intermediate Nodes (TERRAIN) was proposed in [48] to solve the sparse anchor node problem despite errors in the range measurement. The algorithm is split to two phases: the ***start-up*** phase and the ***refinement*** phase. The start-up phase focuses on the sparse anchor node problem by spreading the awareness of the anchor nodes' positions through the network in order to allow all the nodes to get initial position estimates. The initial estimation is very rough possibly but it is very useful for some nodes to get an approximation to their location. Therefore, the refinement phase can use the results of the start-up phase to improve their initial position estimations. The Hop-TERRAIN [69] algorithm is similar with the DV-Hop method, both of them are landmarks-based algorithm, but with a start-up phase the Hop-TERRAIN is expected to achieve better accuracy.

Note that most of the positioning algorithms mentioned before rely on the physical distance between nodes, except the hop-related ones such as Hop-TERRAIN and DV-Hop [71]. Three approaches are used in radio system to measure distance: Signal Strength, Angle of Arrival (AoA) and Time of Arrival (ToA & TDoA) [72]. [58] proposed a user location service in MANET by implementing the radio propagation models. Using these models, the distance can be calculated according to the signal power even when the obstructions and orientations exist in the network. AoA requires directive antennas or antenna arrays in each MN [72] to detect the source position of incoming signal, which is not feasible in current equipment. Also, it is not advisable to use AoA in microcells. In microcells, because the node will be surrounded by some local scatters and the signals arrive the BS can have a broader range of angles. Using ToA, with synchronised time, when the signal gets to the destination, the receiver can measure the duration of the signal from the source. Basically, the distance can be obtained by $dist = velocity \times duration$.The disadvantage of ToA is that it requires every node to act as a transponder in which the processing delays exist and the non-LOS propagation can also introduce the errors. However the shortcoming can be avoided by measuring the time difference instead of the absolute time. Corresponding to a constant time difference of arrival for two nodes, the time differences define the hyperbolas, with foci at the nodes, on which the Mobile Station (MS) must still lie. The intersection of hyperbolas then provides the location of the MS. This method is often called the time difference of arrival (TDoA) [72].

3.2.2 Mobile Node Positioning Algorithm

The mobile ad hoc network can be constructed anywhere. Accordingly all the algorithms implemented in MANET must be flexible in any environment. GPS can be used as an easy way to get position, but for the ad hoc nodes, several points must be concerned: The GPS devices are not popularly used by the public yet. Second, the battery used in normal mobile equipment cannot support the GPS receiver for a long time. Inaccessibility is the third issue that cannot be avoided in MANET. It cannot be guaranteed that the mobile node can get the GPS signal anywhere and anytime. Forth, the precision GPS give us ranges from 5m to150m. Mobile ad hoc networks will be largely used in the indoor occasions, such as in a meeting, an exhibition, etc. If each node's position is relied on the GPS signal, there must be some mobile nodes appearing at the same location because of the low precision.

The algorithms described in this Chapter are designed to be suitable to both GPS-free and GPS-aided cases. In other words, this solution for the mobile node positioning is independent on the GPS.

To simplify this research, the following assumptions are adopted in this work:

Every node in the network has the same configuration, i.e. they have the same software and hardware specification as mentioned in Chapter 2;

Omni-directional antenna is used in any nodes with identical physical properties;

The mobility of the mobile node is limited to a certain threshold.

Usually the GPS signal includes 3-Dimention (3-D) and Time information; in the work here only 2-Dimention (i.e. the X and Y locations) is used. Therefore, there might be some 3-D to 2-D converting pre-procedures required before this algorithm is implemented.

3.2.3.1 MOBILE NODE POSITIONING WITH GPS EXISTS

Several terms which will be used in following sections are defined here:

- **Neighbour**: if node *A* can communicate with node *B* directly, i.e. the packets transmitted between these two nodes are just only require one hop; we said that node *A* is a neighbour of the node *B*;

- **Neighbour's distance**: as mentioned before, it is the geographical distance between any pair of neighbours. It assumes that this distance can be achieved by the method of ToA (TDoA), etc.
- **Reference Coordinate System (RCS)**: is defined by selecting three nodes in the network. When it is spread to the entire network, it becomes the Mobile node Positioning (MP) Coordinate System;
- **MP Coordinate System**: is the final GPS-free coordinate system to be achieved, the location of each node (**MP location**) in this domain is independent on GPS.
- **Fake-GPS Coordinate System**: is the final GPS-synchronized coordinate system to be achieved if certain condition can be met. Ideally, this coordinate system should be close to the real GPS coordinate system;
- **GPS Coordinate System**: is the real position system defined by the GPS system;
- **Offset**: when the RCS & MP Coordinate System is stabilized, the offset of X, Y coordinates will be used in order to shift to the Fake GPS coordinate;
- **Rotation Angle**: the RCS & MP Coordinate Systems have different orientation with the Fake GPS Coordinate, and the rotation angle are used to adjust them to have identical orientation;
- **GPS-node**: the MN that can receive the GPS signal directly;
- **MP-node**: the MN that has got its RCS domain location (MP location);
- **Fake-GPS-node**: the MN that has got its location in the Fake-GPS domain.

3.2.3.1.1 Reference Coordinate System (RCS)

Initially, the neighbours of node i can be detected by using HELLO packets. N_i is used to denote the set of neighbours which belong to node ***i***; Then the distances between the neighbours and node i can be calculated, denoted as D_i . The full procedure performed at each node is listed here:

- Detect the neighbours (N_i) of node ***i*** by HELLO message
- Calculate the distance between neighbours and itself (D_i)
- Broadcast these distances to each neighbour

After all the nodes perform these procedures, each node in the network should know almost all the distance between his one-hop (two-hop) nodes and its own. The preliminary step is done.

To generate the RCS, the nodes *j*, *k* are chosen (the distance between them is $d_{jk} \neq 0$), and $d_{ij} + d_{jk} \neq d_{ik}$, $d_{ik} - d_{jk} \neq d_{ij}$, $d_{ik} + d_{ij} \neq d_{kj}$ must be satisfied, i.e. the nodes *i*, *j*, *k* cannot be located on the same line. Node *i* is defined as the centre of this coordinate system, i.e. the coordinates of node *i* is $x_i = 0$, $y_i = 0$. For the *j*, *k* we choose one of them (here *j* is chose as an example, to convert it to Fake-GPS coordinates) to lie on the *X* Axis with positive sign. Figure 3.1 shows the initialised Reference Coordinate System (RCS). Two nodes now have been located:

$$x_i = 0, y_i = 0$$

$$x_j = d_{ij}, y_j = 0$$

In the triangle Δijk, we can use the cosine rule to get the $\angle kij$ as the d_{ij}, d_{ik}, d_{jk} are known already.

$$\angle kij = \arccos \frac{d^2_{ij} + d^2_{ik} - d^2_{jk}}{2 d_{ij} d_{ik}} \tag{3.1}$$

Now, the coordinates of node *k* can be obtained by the following equations:

$$x_k = d_{ik} \cos \angle kij \tag{3.2}$$

$$y_k = d_{ik} \sin \angle kij \tag{3.3}$$

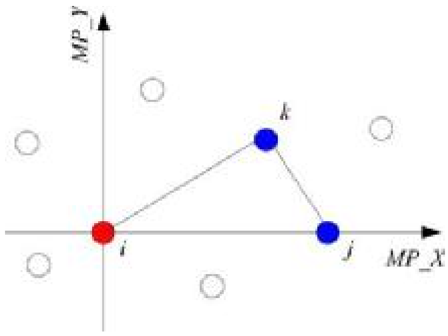


FIGURE 3.1 INITIALISATION OF THE REFERENCE COORDINATE SYSTEM (RCS)

3.2.3.1.2 Offset & Rotation Angle

Section3.1.3.1.1 has described how to generate the Reference Coordinate System, but the real case is much more complicated because the aim is to convert the MP Coordinate to Fake-GPS Coordinate as showed in Figure 3.2.

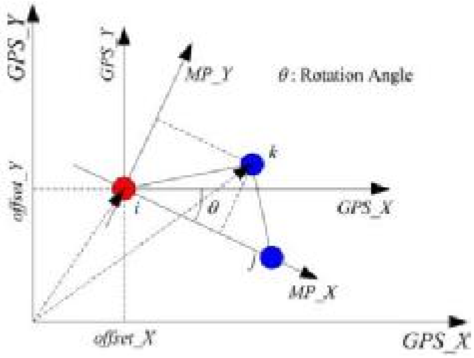


FIGURE 3.2 THE CALCULATION OF OFFSET & ROTATION ANGLE

First of all, the offset and rotation angle conversion needs to be worked out. In order to achieve this, two nodes out of the three initial nodes must be GPS-nodes, one for the offset counting, the other for the rotation counting. A GPS-node ***i*** is chosen as the centre of the RCS, thus the offset is the value of GPS location of ***i***:

$$\begin{aligned} offset\_X &\;\; X_{i\_gps} \\ offset\_Y &= Y_{i\_gps} \end{aligned} \tag{3.4}$$

then another GPS-node is chosen as the neighbour ***k*** in RCS, thus according to the coordinate rotation equations:

$$\begin{pmatrix} X \\ Y \end{pmatrix} \quad \begin{pmatrix} \cos\theta & \sin\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} X_r \\ Y_r \end{pmatrix} \tag{3.5}$$

where X_r, Y_r are the original location, X, Y are the location after the rotation, and θ is the rotation angle. Now:

$$\begin{aligned} fake\_gps\_X &= (tp\_X * rotation\_\cos + tp\_X * rotation\_\sin) + offset\_X \\ fake\_gps\_Y &\;\; (tp\_Y * rotation\_\cos - tp\_Y * rotation\_\sin) + offset\_Y \end{aligned} \tag{3.6}$$

and the cosine and sinusoidal value of rotation angle can be derived:

$$\begin{aligned} delta\_x &\;\; fake\_gps\_X - offset\_X \\ delta\_y &= fake\_gps\_Y \;\; offset\_Y \\ \cos\_value &\;\; (tp\_X * delta\_x + tp\_Y * delta\_y)/(delta\_x^2 + delta\_y^2) \\ \sin\_value &= (-tp\_X * delta\_y + tp\_Y * delta\_x)/(delta\_x^2 + delta\_y^2) \end{aligned} \tag{3.7}$$

If the RCS has the similar direction as showed in Figure3.2, the offset and rotation angle can be used straightforward to solve the conversion problem, but it is not always the case. Figure 3.3 shows another possible direction of RCS.

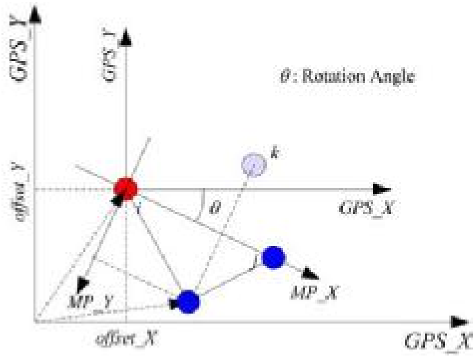


FIGURE 3.3 THE Y-FLIP OPERATION BEFORE THE CALCULATION OF THE OFFSET & ROTATION ANGLE

In this special situation, the rotation Equation 3.6 is useless because it is impossible to rotate a RCS coordinate system to a GPS coordinate system. This issue can be solved by flipping the MP_Y value of node *k*, i.e. inverting the Y axis of RCS. The effect is that node *k* move to k', then the situation is back to the same as Figure 3.2.

So in that case the RCS actually has to be determined first. As mentioned before, a GPS-node is chosen as node *k*, then its MP position can be obtained and the GPS location is a known figure. As soon as the cosine and sinusoidal values of rotation angle are calculated, they can be used back to Equation 3.6 for the calculation of the Fake-GPS location. Comparing this with the real GPS location, it can be determined whether the *Y* value of *k* should be flipped.

When the RCS is generated, node *i* should broadcast a short packet to the network and declare that it is the centre of this RCS. The packet should contain its address, the offset, the rotation value and sequence number for the times of position updates.

3.2.3.1.3 Mobile nodes Positioning

From section 3.1.1 & 3.1.2 the position of node *i* and its two neighbours *j* and *k* have been determined. The way to get the MP position of all other neighbour nodes will be discussed in this section.

a. Neighbour-Area Nodes of Centre node

As shown in Figure 3.4, node $p \doteq N_i, p \neq j,k$ for which the all the distances between any two nodes are known, then the triangulation can be used to count the MP position of node *p*.

$$x_p = d_{ip} \cos \angle jip$$

$$y_p = \pm d_{ip} \sin \angle kip$$

where $\angle kip$ can be obtained by using the cosine rule

$$\angle jip = \arccos \frac{d^2_{ij} + d^2_{ip} - d^2_{pj}}{2 d_{ij} d_{ip}}$$

The problem remains is how to decide the sign of value y_p. Regarding the position of node *p*, four possibilities exist as illustrated in Figure3.4.

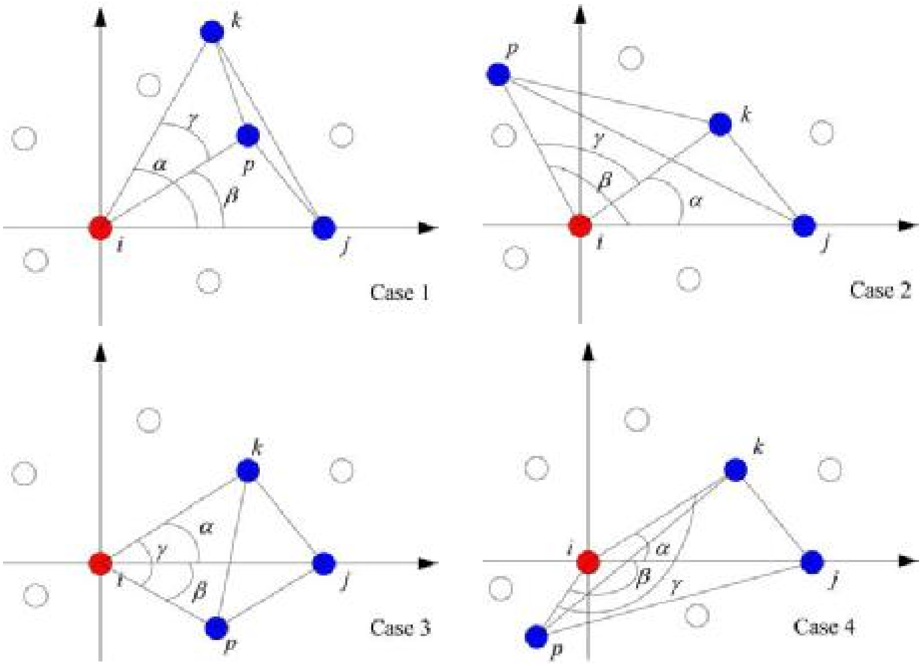


FIGURE 3.4 FOUR POSSIBLE CASES IN NEIGHBOUR-AREA OF THE CENTRE NODE

for case 1 & case 2, they have

$$\alpha - \beta = \gamma \text{ or } \beta - \alpha = \gamma$$

for case 3 & case 4, they have

$$\alpha + \beta = \gamma$$

where

$$\alpha = \arccos \frac{d^2{}_{ij} + d^2{}_{ik} - d^2{}_{jk}}{2 d_{ij} d_{ik}}$$

$$\beta = \arccos \frac{d^2{}_{ip} + d^2{}_{ij} - d^2{}_{jp}}{2 d_{ip} d_{ij}}$$

$$\gamma = \arccos \frac{d^2{}_{ik} + d^2{}_{ip} - d^2{}_{kp}}{2 d_{ik} d_{ip}}$$

Based on the value of these three angles, the sign of node *p* can be judged, i.e. case 1 and case 2 will give the positive sign to MP_Y_p and case 3 or 4 will be given negative sign.

Until now, all the location of the neighbours around centre node *i* are calculated by the centre.

b. Non-Neighbour-Area Nodes of The Centre Node

For non-neighbour-area node $q \notin D_i$, the centre node cannot be relied on any more because the node only has the distances of one or two hops to itself. Therefore, the neighbour's location becomes the only reliable reference for each node.

Several flags will be kept in each node to indicate the positioning status and must be set after each update. Each node keeps a list of the neighbours as well as the positioning status of its neighbour to have the information of how many GPS-node around, how many MP-node around, etc. When this procedure is finished, all the neighbour nodes of the centre will have MP-node flags set and broadcast them the neighbours.

There four cases have to be considered and the solutions are also given as follows.

Three GPS Neighbour Nodes Around

As illustrated in Figure 3.5, node *B* located in the non-centre area in MP coordinates.

When the update time comes, node *B* check its neighbour lists, finds out how many neighbours it has, and check their location status flags too.

For example, MP-node nodes $C, D, E \in N_B$ are found and the distances d_{CD}, d_{BC}, d_{BD} are known to node *B*. The location of node *B* is set in real GPS coordinates to be (x_B, y_B), and the node C, D has $(x_C, y_C), (x_D, y_D)$ GPS location respectively. Then the following equations should be satisfied:

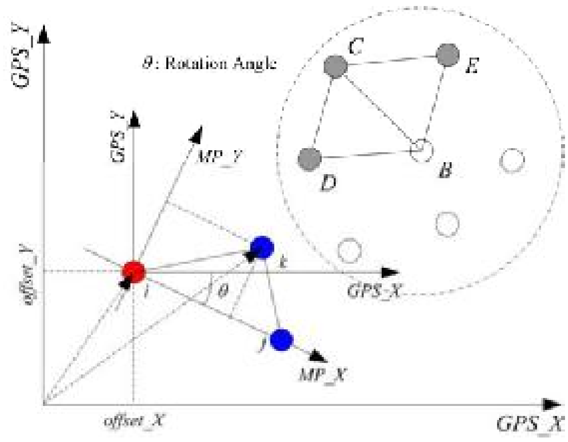


FIGURE 3.5 THE CALCULATION OF THE POSITIONS OF MOBILE NODES IN NON-NEIGHBOUR-AREA OF CENTRE NODE

$$\begin{aligned} \sqrt{(x_B - x_C)^2 + (y_B - y_C)^2} &\quad d_{BC} \\ \sqrt{(x_B - x_D)^2 + (y_B - y_D)^2} &\quad d_{BD} \end{aligned} \tag{3.8}$$

and:

$$x_B \quad \frac{-coef\_b + \sqrt{coef\_b^2 - 4 * coef\_a * coef\_c}}{2 * coef\_a} \tag{3.9}$$

$$y_B = \frac{a \quad 2 * c * x_B}{2 * b} \tag{3.10}$$

where:

$$coef\_a = 4(b^2 + c^2),\ coef\_b = 8bcx_C \quad 8b^2 y_C \quad 4ac$$

$$coef\_c = a^2 \quad 4abx_C + 4b^2 x_C{}^2 + 4b^2 y_C{}^2 \quad 4b^2 d_{BC}$$

$$a \quad d_{BC}{}^2 - d_{BD}{}^2 + x_D{}^2 - x_C{}^2 + y_D{}^2 - y_C{}^2$$

$$b = x_D \quad x_C$$

$$c \quad y_D \quad y_C$$

Figure 3.6 shows its two possible locations:

The correct location of node *B* must satisfy the following equation based on the distance d_{BE}:

$$\sqrt{(x_B - x_E)^2 + (y_B - y_E)^2} \quad d_{BE} \tag{3.11}$$

Accordingly location $B^{'}$ on Figure 3.6 can be disregarded. Node *B* then sets its Fake-GPS flag and attaches it in the next HELLO packet to indicate that it has Fake-GPS location.

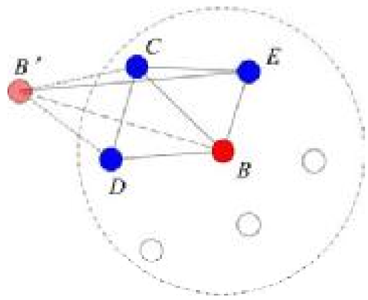


FIGURE 3.6 ILLUSTRATION OF TWO POSSIBLE LOCATION DERIVED BY EQUATION 3.8

The Equation 3.8 could have no solution. Because the values of d_{BC}, d_{BD} and d_{CD} are all estimates and these estimates might be wrong, it could raise two particular cases as shown on Figure 3.7 which causes no solution to Equation 3.8.

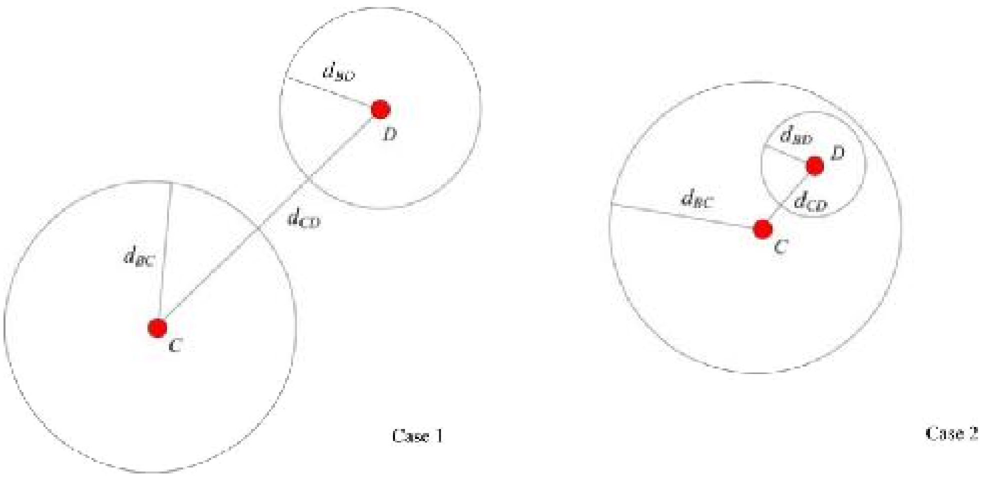


FIGURE 3.7 TWO POSSIBLE CASES WHEN THERE IS NO SOLUTION TO EQUATION 3.8

In these two situations, there are no intersections for the two circles *C* and *D*, i.e. it is impossible to find a node *B* with distance to *C*, *D* equal to d_{BC} and d_{BD} respectively. To avoid such cases, the following conditions must be verified before the position calculation:

1. $d_{CD} <= d_{BC} + d_{BD}; d_{BC} <= d_{CD} + d_{BD}$
2. $coef\_b^2 - 4 * coef\_a * coef\_c >= 0$ in Equation 3.9

If the inequality can not be satisfied, one of the two neighbours must be reselected.

– **Three Fake-GPS Neighbour Nodes**

If node *B* fails in discovering three GPS-nodes, it has to reduce the positioning requirements. The three neighbours can be either GPS-nodes, or Fake-GPS nodes. The location used in Equation 3.8 and 3.11 depends on the neighbour's location status. When the positioning procedure ends, the node becomes the Fake-GPS node too.

Three MP Neighbour Nodes

This is almost the same situation described in previous section, the only difference here is that the node *D* has three MP-nodes around instead when it checks its neighbour list. The solution is to use the MP locations of its three neighbours in Equation 3.8 and 3.11.

– **Two MP Neighbour Nodes**

In high density MANET, the solutions for three GPS-node neighbours or three MP-node neighbours should be good enough to give high precision and low uncertainty. However in a lower density wireless network, when only two MP neighbours can be found, the node has to guess its position thus it can not guarantee whether the results are correct or not.

When the node gets the two possible positions by Equation 3.8, it will calculate the distance between *B* & *B'* with RCS centre node *I*.

$$\sqrt{(x_B - x_I)^2 + (y_B - y_I)^2} = d_{BI}$$

$$\sqrt{(x_{B'} - x_E)^2 + (y_{B'} - y_E)^2} = d_{B'E}$$

According to the algorithm used for the broadcasting positions, usually the nodes closer to the centre will get its location earlier. So the solution is that the location with longer distance is always assumed the right one. Note that it is only a compromised approach.

Once the node gets the MP location, the relevant location status flag will be set and broadcasted to the neighbours in the next HELLO message.

3.2.3.1.4 Conversion from MP Coordinates to GPS Coordinates

As mentioned in the previous section, each MP location must be converted to GPS coordinate by using the offset and rotation angle which are broadcasted by the centre node when the RCS is initialized. The conversion equation is Equation 3.6 in section 3.1.3.1.2.

3.2.3.1.5 Reference Centre Node

In this algorithm, the choice of Reference Centre Node, i.e. the choice of node *i*, plays a very important role which determines the efficiency of the whole algorithm. However, the topology of the network could change at any time. How to maintain and update the Reference Centre Node is another issue should be dealt with.

a. Reference Centre Node Initialization

To choose node *i* efficiently, the following algorithm is implemented:

- The density of each node will be counted and broadcasted to the network.

The density can be defined by many standards, for simplicity, the metric known as degree of association stability is used, i.e. amount of neighbours. Each node periodically sends HELLO message to its neighbours to tell them its existence. When the neighbour receives the beacon, it will update its associability field by increasing it by 1, and then the amount of neighbours can be counted during this period. Once all the nodes get the parameter, they will broadcast the density factor to the network.

- The lower density nodes will be slaved by the higher density nodes

Finally, the nodes with lower density factor will stop broadcasting as long as they know there is a neighbour around it with higher density. The higher density factor as well as that neighbour's id will be stored. In the next HELLO period, the new density factor and neighbour id will be broadcasted instead. After a fixed time, only the highest density node will be kept by all the nodes in the network. If several nodes have the same density, one of them will be selected randomly to be the centre of RCS (in the simulation, the node with smaller id will be kept assuming it has higher privilege).

Figure 3.8 gives a simple example of choosing the centre node. Node *D* and Node *E* have the associability of 6, but because the *D* has a smaller ID, the coordinate created by *E* will be disregarded. Again, node *C* has a higher associability than node *D*, and the coordinate created by *D* will be disregarded. Finally, node *C* will be chosen as the centre area.

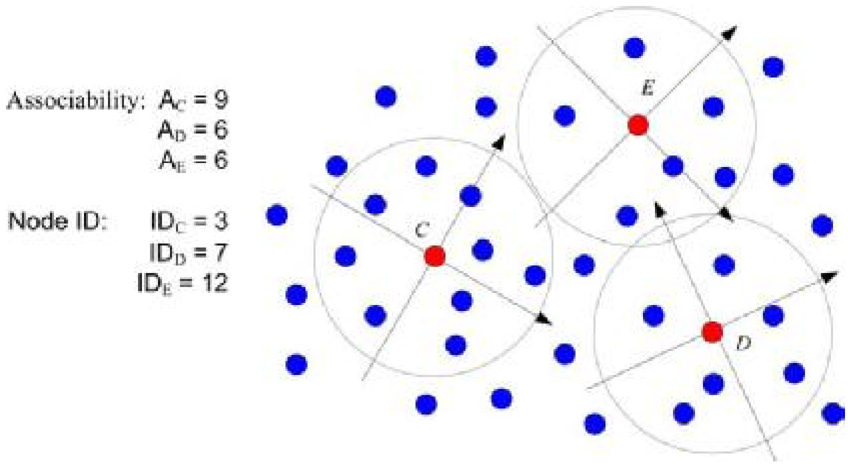


FIGURE 3.8 AN EXAMPLE NETWORK TO DEMONSTRATE THE CENTRE NODE INITIALIZATION

b. Reference Centre Node Maintenance

The topology of mobile ad hoc networks changes thus the coordinate systems have to be updated from time to time. The following points are relevant:

- The New Centre will be chosen periodically;
- Every GPS-node with at least one GPS-node neighbour can declare that it wants to be the centre of the system when it finds its associability exceeds the threshold pre-defined. But after a period of time, only one set of associability and node ids will be kept by each node.
- When the new updating time arrives, the degree of association stability in each node should be cleared and recounted;
- The HELLO message should contain a sequence number that is increased by 1 in each update time to indicate the times of the update. The node receives the HELLO message, checks the sequence number then compares it with its own. If its own number is smaller than the received one, this means newer positioning information is coming, this node should continue to check other information like centre id, associability, offset, etc. If not, this node will do nothing for the positioning.
- The node closest to the old centre should be chosen, therefore the new location of every node will not be dramatically changed compared with the old location.

3.2.3.2 GPS-Free Mobile Node Positioning

A worst case is that there is no GPS-node with one GPS-node neighbour that can be found during the positioning time, or it is known in advance that wireless network can not connect to the GPS satellites. In other words, it is a completely GPS-free environment.
This algorithm is still suitable for this situation. The centre can be chosen without the existence of GPS-nodes. The Reference Coordinate System can be stabilized by any three nodes and the neighbours of centre can get its MP location using the same positioning procedure. The difference here is that the non-neighbour nodes only need its MP-node to update its MP location. The position correction procedure is not required any more.

3.1.3.3 From 2-D Positioning to 3-D Positioning in MANET

3-D positioning is a very interesting and promising topic in MANET. GPS can provide 3-D position information. [74] presented a detailed derivation for the 3-D positioning. With that algorithm, the 3-D location can be obtained given the locations of four fixed stations. The algorithm for the 2-D system proposed in this research is scalable to 3-D positioning.
Generally, three points can define a plane. Extending to 3-D system, the three points *i*, *k*, *j* is denoted as:

$$i(x_i, y_i, z_i) \qquad j(x_j, y_j, z_j) \qquad k(x_k, y_k, z_k)$$

then the following equations can be used to calculate the forth node's $p(x_p, y_p, z_p)$ position:

$$\begin{aligned} d_{ip} \quad & \sqrt{(x_i - x_p)^2 + (y_i - y_p)^2 - (z_i - z_p)^2} \\ d_{kp} = & \sqrt{(x_k \quad x_p)^2 \mid (y_k \quad y_p)^2 \quad (z_k \quad z_p)^2} \\ d_{jp} \quad & \sqrt{(x_j - x_p)^2 - (y_j - y_p)^2 - (z_j - z_p)^2} \end{aligned} \tag{3.12}$$

With three unknowns and three equations, it is possible to work out the value of x_p, y_p, z_p. The problem is that there is a square root in the calculation and the solution to the unknowns is not unique. As discussed in the 2-D positioning, there will be two possible points whose locations can satisfy the three equations, it must be established which one has the correct position. One solution is to find a forth neighbour and take the forth distance equation into account. The only issue remaining is how to get the offset and rotation angle once the Reference Coordinate System is generated. This topic needs further research. Most of solutions described in the previous sections, such as HELLO message broadcast, centre node maintenance, etc. can be used to enable 3-D positioning.

3.2.3.4 The Location Estimation Error

The possible estimation errors in this algorithm are discussed in this section. The positioning algorithm is then optimised to cope with some of these issues to some extends.

3.2.3.4.1 The Non-Line-Of-Sight Problem in ToA (TDoA)

Nowadays, the ToA (TDoA) is implemented in cellular communication systems. If the Non-Line-of-Sight (NLOS) error exists, this will possibly occur in the mobile ad hoc network too. Note that the Base Stations (BSs) in the cellular system have fixed position, which can reduce the location estimation to an acceptable range. As mentioned before, this algorithm highly depends on the distance between the neighbours, the situation in mobile ad hoc network is more complex than the cellular system and the positioning results could be worse.

3.2.3.4.2 The Error Accumulation

As described, except for the centre area node, all other nodes should estimate their locations according to their neighbours. Therefore, it is possible for errors to accumulate. For example, if a NLOS error happens in the centre area, then nodes in that area will estimate a wrong position. However the nodes in non-centre area have no idea about the NLOS error and will calculate this position based on the wrong position of the nodes in the centre area. The error will then be broadcasted to the entire network, and all the location will be useless.

3.2.3.4.3 Low Connectivity Node

The position of a node is calculated by using its neighbours. So the associability (connectivity) of nodes is a very important factor which can influence the performance.

Figure 3.9 shows a special case which can happen in MANET. If node ***i*** is selected to be the centre of MP coordinate, the positioning process is called in nearest nodes to farther nodes. But, for node ***C*** with very low connectivity, only the node ***D*** has got the MP location, so it becomes difficult for ***C*** to get the position, and node ***B*** and ***E*** will suffer the same issue. This issue needs to be addressed in future work.

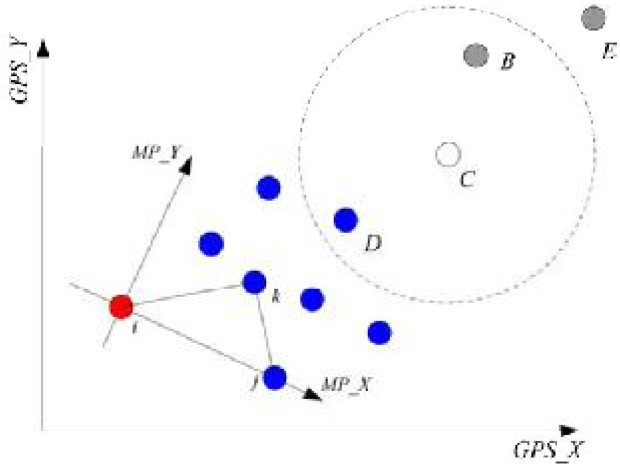


FIGURE 3.9 ILLUSTRATION OF LOW CONNECTIVITY ISSUE IN MANET

3.3 LOCATION-BASED ROUTING IN MANET

As an extension of the mobile node positioning, a new location-based routing protocol is also proposed, called Location-Label-Based Routing (LLBR) which couples with the positioning algorithm described in the section 3.2. The novelty here is that it is the first location-based protocol with the integration with positioning as well as location discovery. Note that the consistency between the routing and positioning is the main interest in this research. The detailed approach is described in this section but the LLBR still requires further modification and optimization on routing. The simulation results and some comparison work are provided in Chapter 6, along with the analysis of the performance.

3.3.1 RELATE WORKS

Due to the changeable topology of MANET, the routing protocol used by the MNs has a significant effect on the overall performance of the network. The routing protocols for a MANET can be can be classified as ***proactive*** and ***reactiv***e (see Figure 2.5) depending on the MN's reaction to the topology change. A MN running a proactive routing protocol will broadcast a routing-related message to its neighbours who will use the information to update their own routing table then broadcast more routing-related messages to others. This process occurs in each MN and finally all the MNs will keep a routing table with records of all the possible destinations. Typical proactive protocols proposed include Destination Sequenced Distance Vector (DSDV) [65], the Wireless Routing Protocol (WRP) [36] and Routing Information Protocol (RIP) [37]. In some sense, the proactive protocols are not intelligent or more efficient than the reactive ones. Even if a MN does not need the routing information, the routing-related messages must travel through the network. Therefore, the traffic caused by the routing messages could be very heavy as the network scales. The bandwidth is wasted by unnecessary routing information.

Unlike the proactive protocols, in reactive protocols the routing information is only been exchanged when the source node needs it. AODV [1], DSR [66] and the Signal Stability-based Adaptive Routing (SSA) [38] are the typical reactive protocols. Routing in reactive protocols typically consists of three stages: Route Discovery, Data Transmission, and Route Maintenance. Route Discovery deals with how to request for routes to the destination and how to respond to the request from the source; Data Transmission deals with how to transmit the data from the source to the destination, i.e the format of the packet and routing table. In DSR, the data packet forwarded should include the full route to the destination, but the AODV data packet just needs the next-hop address. Route Maintenance solves the route breakage issues and keeps the routing table up to date.

Most of the routing protocols are discussed in [76]. However, this classification of *proactive* and reactive routing algorithm is not really our interest. The routing protocol used in MANET can be further classified by whether they use location information or not. With the aid of location information of MNs, more protocols have been proposed as a variant of proactive or reactive routing protocols. Two popular protocols are LAR and DREAM which have been introduced in Chapter 2.

Generally to say, there are three strategies used in the location-based routing protocol [75]: Directional Strategy (DS), Hierarchical Strategy (HS), and Proxy Strategy (PS). LAR, optimizations of LAR [73] and DREAM [68] are the typical ones using DS. In these proposals a packet is forwarded to all the nodes in the direction of an area associated with the destination. These protocols can work as a complementary algorithm to some non-geographic protocols to enhance the performance when some route failure happens. HS is a more scalable strategy since it uses hierarchical knowledge. An example of this protocol is GPS-Based Addressing and Routing presented in [77] which defines different classes of MNs, such GeoRouter, GeoNode and GeoHost. Each class of MN has a different level of hierarchy and behaves as router, end user, etc respectively. PS has an advantage especially to the nodes unlikely to obtain their location. In this case, a nearest node will be select by them to act as a proxy to forward the packets. More detail about PS can be found in [78].

The LLBR protocol described in next section is quite similar with the LAR and DREAM. As illustrated by Figure 3.10, the basic routing idea in the LAR and DREAM is to reduce the request (route) zone as much as possible. The another advantage in DREAM is that it much concerns about the mobility and distance effect in which way the location information is fresh and achieves good packet delivery rate.

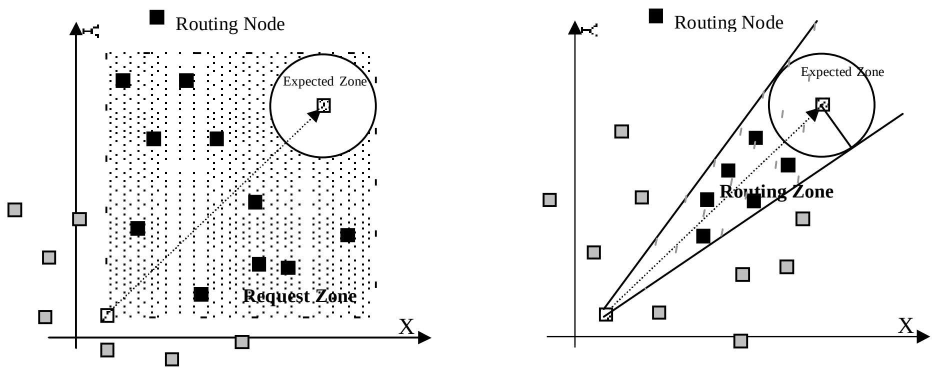


FIGURE 3.10 ILLUSTRATION OF LAR (A) AND DREAM (B) ROUTING PROTOCOLS

3.3.2 LOCATION-LABEL-BASED ROUTING (LLBR) PROTOCOL FOR MANET

Two different routing algorithms are proposed for two situations: Local Area Routing and Remote Area Routing.

3.3.2.1 Local Routing Algorithm (LRA)

The one-hop area is regarded as the Local Routing Area (LRArea) of node *i*. LRA is the non-location-based part of LLBR, note that:

- In a high density MANET, GPS (Fake-GPS) precision or MP precision limit may corrupt the algorithm as mentioned at the beginning of section 3.1.2 in GPS-aid case;
- Due to the mobility of MANET, there is a trade-off between the coordinate updating frequency, the traffic load of the network and the routing efficiency, i.e. to get a more precise current position, the interval must be reduced between the continuous position updating procedures in order to increase the location-based routing efficiency, whereas this also increase the traffic load and overhead in the network;
- Usually, the small HELLO message is broadcasted with much higher frequency than the frequency of the position update. So the neighbour list kept in each node can always be trusted more than the location information.

As shown in Figure 3.11, node *D* has moved to location *D'* when the packet gets to its neighbour *K*, if *K* still use the location-based routing algorithm, the packet will get lost. However since the new location *D* is still close to *K*, when *K* checks its neighbour list, it will find *D* still in the list, then what *K* can do is just broadcast the packet to *D*. Thus the performance could be improved.

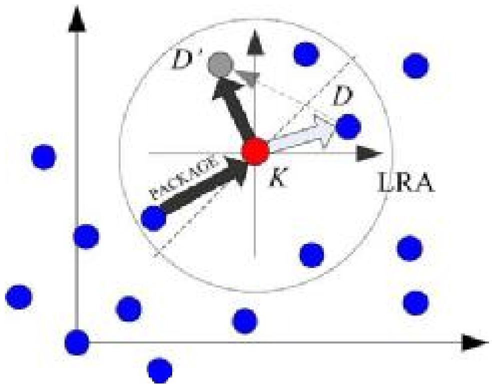


FIGURE 3.11 ILLUSTRATION OF THE ROUTING PROCESS USING LOCAL ROUTING ALGORITHM (LRA)

The following are the two key points of the algorithm used in LRA:

- In each fixed interval, every node sends the HELLO message to its neighbour; the neighbour's basic information should be stored.
- When the receiver gets the packet, it checks if the destination is in its neighbour list. If yes, it means that the packet gets to the LRA area of the destination and location

based routing algorithm will not be used. The TTL field in the packet head is set to 1 which only allows this packet to be forwarded by one hop.

3.3.2.2 Remote Routing Algorithm (RRA)

In the Remote Routing Algorithm (RRA), a Direction Indicator Byte (DIB) is defined and added in the Routing Request messages to indicate the direction they should be transmitted. Figure 3.12 illustrates the detailed definition:

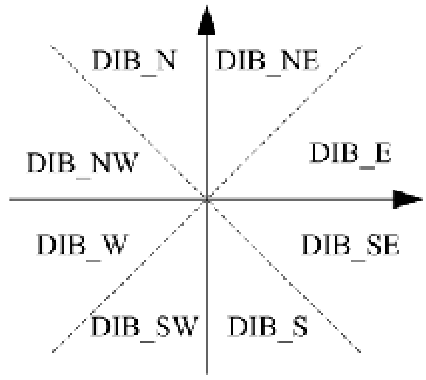


FIGURE 3.12 EIGHT DIRECTIONS INDICATED BY THE DIRECTION INDICATOR BYTE (DIB)

The coordinate was divided into eight quadrants (directions), and eight bits (one byte) are used to represent these directions respectively.

Figure 3.13 shows the format of the DIB:

7	6	5	4	3	2	1	0
SE	S	SW	W	NW	N	NE	E
1 Byte							

FIGURE 3.13 THE FORMAT OF DIRECTION INDICATOR BYTE (DIB), EACH BIT IS USED TO REPRESENT ONE DIRECTION

Before the nodes transmit the message, it will calculate the direction and set the corresponding bit to 1, and the receiver at the next hop will check whether it lies in the direction. If yes, this node will handle the message, or it will drop it; moreover, if the neighbour list in this node has already kept a record of the destination node, the LRA will be used for routing.

The Figure 3.14 shows a demonstration of RRA. If the source node *S* needs to communicate with destination node *D*, *S* calculates the angle $\angle DSX$.

$$\angle DSX = \arccos\frac{y_D - y_S}{x_D - x_S}$$

In this case the angle $\angle DSX$ is larger than 45° but less than 90°, the corresponding direction is NE. Therefore the bits in DIB is set to 00000010 and this is added into the Routing Request message which is broadcasted to the neighbours of node *S*. Node *A* receives the packet and checks its destination. It turns out that the destination is not contained in its neighbourhood list, which means the RRA should be used. Because node *A* has the location information of *S*, it receives the message and counts the angle $\angle ASX$ and gets his DIB 00000001 which does not equal to the DIB in the message, so this message will be disregarded by node *A*. But node *B* gets the same DIB, so it will respond to the routing request and forward the message to its neighbours. According to the topology showed in the Figure 3.14, the message will be transmitted along the route in black and reaches the node *F*. Similarly, node *F* will check its neighbourhood list, but this time it will notice that *D* is its neighbour. Therefore, the LRA described before will be used instead.

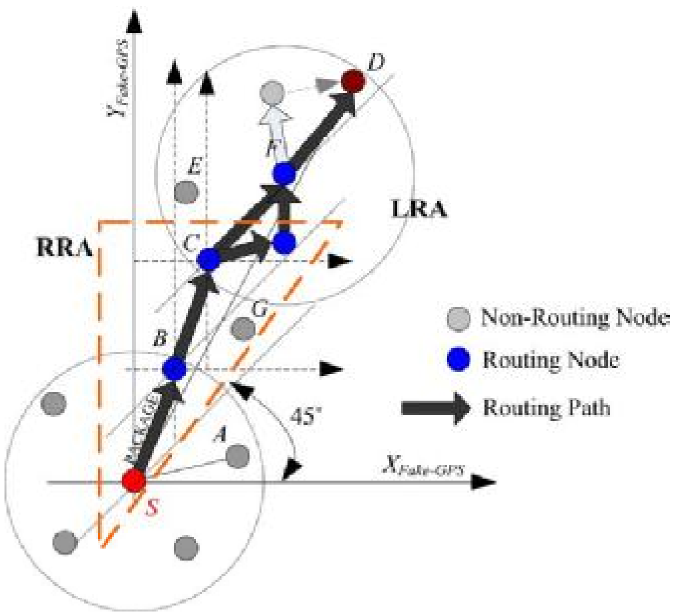


FIGURE 3.14 ILLUSTRATION OF THE ROUTING PROCESS USING REMOTE ROUTING ALGORITHM (RRA)

The Route Request Area of RRA is marked in Figure 3.14. It is smaller compared with the protocol LAR shown in Figure 3.10.

3.3.2.3 Description of The Location-Label-Based Routing (LLBR)

In the current version of LLBR, there are three stages: Positioning, Location Propagation and Data Forwarding. The Positioning Stage along with the Location Propagation Stage is the main feature that differentiates it from other location-based routing protocols which assume the location information of each node pre-exists. The Positioning Stage is the implementation of the Positioning Algorithm proposed in section 3.2. Routing protocols use the HELLO message to maintain the Neighbour Table. Due to the high transmitting frequency of HELLO message, large packet can easily cause the traffic collision and terribly harm the total performance of protocol. Therefore, a new packet type called Positioning Packet is created which includes all the necessary position-related information and the HELLO message is kept as small as possible. The first Positioning Packet is initiated by the centre node, and then it is relayed by all the MNs in MANET. Any MN received the Positioning Packet will check its location status and decide which procedure must be taken. Any node that has a Fake_GPS and MP location will enter the Location Propagation stage right away. A Location Packet will be broadcasted to the network to inform other nodes of the location status and location details of the source node. Due to the large size of the Location Packet and its flooding essence, it is suggested that the Data Forwarding stage is needed to be postponed for a while until the flooding procedure is deceased because of Time To Live (TTL) field which is decreased by 1 for each hop in the Location Packet. Data Forwarding Stage is the pure routing stage similar with DREAM, the routing logic has been given in previous section. The detailed knowledge of the mechanism in LLBR is given in Chapter 6, illustrated by several flow graphs.

3.4 CONCLUSIONS

In this chapter a new positioning algorithm for mobile nodes is proposed. This algorithm can operate in both GPS-free and GPS-aided environments. GPS coordinates can be calculated if two or more neighbouring nodes have GPS based coordinates, otherwise a relative local location is provided instead, which is sufficient for the routing algorithms.

A novel location based protocol that integrates the self-positioning algorithm as the location discovery solution was discussed in this chapter.

Cooperated with the positioning algorithm, Location-Label Based Routing (LLBR) protocol might be the first location-based routing protocol without external aid on the positioning of mobile nodes. Depending on the routing area, two different routing algorithms are proposed: Local Area Routing and Remote Area Routing. Taking the advantage of the self-positioning algorithm, the innovation in LLBR is that even when there is no GPS signal available for any MN in the network, this routing method is still available because of the existence of Local Coordinate System (LCS).

In theory, the calculations needed for the positioning algorithm and LLBR protocol are simple enough to be performed by a mobile node. However, whether or not they can be performed well in real time still needs further research which can be done by the emulator described in Chapter 7. The movement of mobile nodes can highly influence the performance of the routing protocol. Further research is required as LLBR routing logic does not consider the movement of the destination node enough. If the destination node moves to a new quadrant, the packet can not be delivered by Remote Area Routing method, and it has to be delivered using a packet flooding method. Positioning and Location Propagation stages may result in high traffic collision due to the flooding method. Methods to improve this protocol are discussed in Chapter 8, Conclusions and Future work.

Chapter 4: ENVIRONMENT-AWARE MOBILITY MODEL (EAM)

4.1 INTRODUCTION

With the work of self-positioning and location-label based routing described in Chapter 3, the impact of the mobility of mobile nodes along with the environment on the performance of the network was identified. A new mobility model with the awareness of the environment where the network is deployed is required. This is an essential work in the framework of the research.

Many researchers have shown interest in MANET and many protocols aiming at different issues have been proposed. The performance of these protocols needs to be carefully evaluated before they go to the commercial market. Network simulation plays a very important role in this area, and it is widely used by researchers as a key method for better understanding of the overall performance of MANET.

Self-organisation is the essential characteristics of mobile wireless networks. Mobile nodes within the network can be any moving or fixed objects equipped with antennas. They can be either human beings carrying wireless equipments walking in a mall or gallery, or insects or animals carrying wireless tracking equipments moving in natural environments. This movement is highly dependent on their own mobility factors and the areas they are located. The mobility model describes how the mobile nodes move and is therefore regarded as an important component in the mobile ad hoc network simulation.

As part of the framework in this research, a novel realistic mobility model is proposed. This is called the Environment-Aware Mobility (EAM) model and it is incorporated with the environments where a MANET is deployed. The Environments include environment objects, such as Routes, Junctions, Accessible Areas and Hotspot etc. Signal-blocking issues are also covered in this model by introducing Closed Areas whose boundaries are considered to be obstacles with no radio penetration.

Two examples of EAM are given, the Hotspot model and the Route model to show how

EAM can be used in complex environments. The Hotspot model is used to describe the movement of the mobile nodes when attractive places exist in the simulation area such as popular pictures in a picture gallery. The Route model can be used to construct complex environments in city areas.

Particularly in the city environment, all the mobile nodes are forced to move on roads, and the signal can be easily blocked or weakened by various forms of obstructions. Figure 4.1 demonstrates a common situation in which *Car A* is making a direction change at a junction. The Line-of-Sight connection established between *Car A* at position #3 and *Car B* at position #1 can be blocked by the building #1 when they move to position #4 and position #2, respectively. As a result, this type of network, called an Inter-Vehicle Communication (IVC) network may suffer from low connectivity and a large number of partitions. On the other hand, the node density can be very high in some occasions such as rush hour and the network performance in this case can dramatically deteriorate due to high network collision and contention. The challenge of these IVC systems is thoroughly addressed in [79].

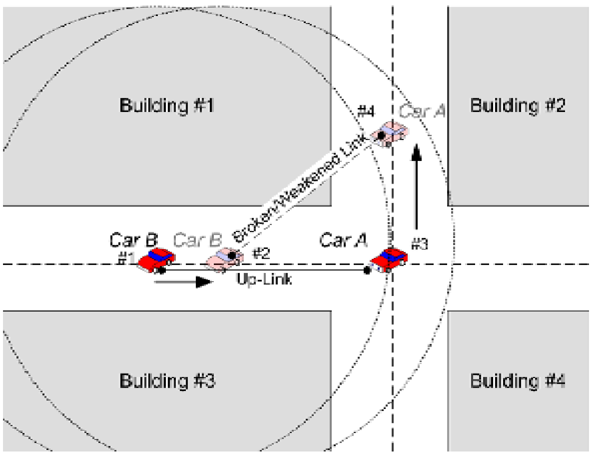


FIGURE 4.1 ILLUSTRATION OF A TYPICAL SITUATION WHERE THE LINK IS EITHER BROKEN OR WEAKEN

Therefore, this chapter addresses the aforementioned issues with a new IVC mobility model based on the Route Mobility model. Unlike others, this IVC model takes more realistic factors into account. For instance, it expands the concept of the mobile nodes so that some special nodes such as pedestrians, traffic lights etc. are included. To help investigate the performance of certain mobile ad hoc networks in more complex environments, two particular City IVC systems are studied. These are the RoadLamp-aided IVC system and the Bus-aided IVC system.

4.2 RELATED WORK

Mobility models are used to describe the movement pattern of mobile nodes. There exists many mobility models proposed for mobile wireless networks. In this section, some of the popular models used in MANET are briefly described.

The categories of the conventional models are illustrated in Figure 4.2. The Entity Models are used to model the movement behaviour of an individual mobile node. The Random Waypoint model [22] is widely implemented by network simulators such as ns2 [51]. In each movement epoch, the mobile node picks a position within the simulation area and moves towards it at a speed distributed in the range [v_{min}, v_{max}]. Instead of moving to the next destination immediately at the time it arrives at the current destination, the mobile node pauses for some specified time and then repeats the procedure. The major drawback is that the nodes tend to move around the centre area so that they are not really distributed into the entire simulation area. The Random Direction [54] model is proposed to cope with this distribution problem. It forces the mobile node to move until it reaches the border of area before it starts its next epoch.

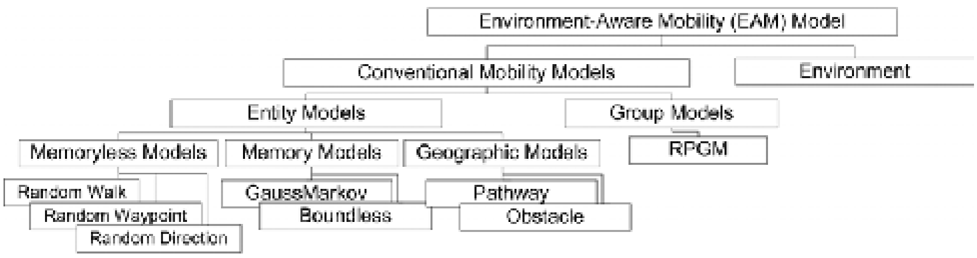


FIGURE 4.2 THE CATEGORIES OF THE MOBILITY MODELS.

The models introduced previously are all considered to be memory-less models since the next movement segment has no dependency on the previous movement regarding either speed or direction. This memory-less feature causes frequent sharp change in speed and direction of movement which is obviously not applicable in a realistic world. Some memory models are proposed. The Gauss-Markov model was first introduced in [55]. In this model, the velocity of the mobile node is assumed to be correlated over time and modelled as a Gauss-Markov stochastic process. The Boundless model [57] is another example of a memory model but with no geographical restriction. Mobile nodes are allowed to cross the boundaries and appear at the other side of the area. The resulting effect is that the simulation area is modelled as a torus instead of a flat area.

In mobile ad hoc networks, there exist many situations where the movements of mobile nodes have some correlation with each other, i.e. mobile nodes have some group behaviour in common. The Group Models have been proposed to present this characteristic. One typical example is the Reference Point Group Mobility model (RPGM) [59]. In RPGM, a logical centre of a group is defined and its movement is used to direct the group-wide movement. Individual members of the group move not purely on a random basis, their movements are also affected by the group movement. RPGM is popularly used in research to depict some scenarios with group behaviors such as avalanche rescue. Other group models can also be found in [2].

The pre-mentioned models all assume that the simulation area is a free space area where mobile nodes can move anywhere inside. They demonstrate the self-organization feature of mobile nodes, but they are not generally applicable, the geographic factors have to be considered. The Pathway models [60] and the Obstacle models [61] partially overcome this disadvantage. The Pathway Model forces each mobile node to move along the shortest path towards its destination. Similar behaviour is also modelled in the Freeway mobility model and in the Manhattan mobility model in [62]. The Obstacle mobility model was first introduced in [67]. Unlike the Pathway model, the Obstacle model defines some obstacles in the simulation area. These obstacles have a signal-blocking effect on the communication of mobile nodes. This model also allows the nodes to change this movement trajectory when obstacles are encountered. Geographic models support more realistic scenarios than Entity and Group models.

Several works have introduced the idea of real-world simulation into MANET simulations. The realistic environment in which the network exists needs to be constructed before running the simulation. [63] provides a way to achieve this by using Auto-CAD, and the realistic world is constructed by implementing the knowledge of the Voronoi diagram in [67]. The movements of the mobile nodes are restricted by the pre-defined arbitrary obstacles and pathways. However, this real-world environment model does not provide a flexible approach to model the mobility variations. The movement trajectory of a mobile node might change from time to time. For example, the mobile nodes move along the pathway then may enter a particular terrain, such as a park where their movements become less deterministic, therefore they might walk in any direction, i.e. the pathway restraints are no longer applied.

As a conclusion, every model mentioned above could be used to model the mobility of mobile node in MANET. They may be used in some particular situations, but none of them is flexible and suitable enough for modelling more realistic scenarios. The Entity Models and the Group Models can co-exist in some scenarios with obstacles. The Obstacle model seems to provide a nice solution to signal-blocking but it leaves characteristics of the entity and group mobility unconcerned. The Obstacles and Paths can be detected in this model but the trajectories to deal with obstacles are simple and not generic. Depending on the roles they play in the environment, mobile nodes can have different mobile characteristics. The fact that environment factors can affect the movement is also overlooked by all of them.

The EAM model proposed in this thesis as shown in Figure 4.2 provides a more general approach to model more realistic mobile ad hoc networks.

4.3 THE ENVIRONMENT-AWARE MOBILITY MODEL (EAM)

The EAM model is designed to model the movement behaviour of mobile nodes in the realistic environments where mobile ad hoc networks exist. The entire environment can consist of several sub-areas which have different restriction on node movements. For example, up-to 70MPH speed limit is allowed for cars in the motorways in UK, but only 30MPH in built-up area; A park can be a very relaxing place where citizens can walk to or stay in anywhere, but there must be limited entries through which they can enter the park; There are also some forbidden places which are not open to the public in the cities. In order to reflect a more realistic environment, these sub-areas are carefully examined, including their properties, characteristics etc. In this research, these sub-areas within the simulation area are abstracted to several so-called Environment Objects (EOs), such as Routes, Junctions and Hotspots etc. The movement trajectory of the mobile nodes is correlated with the sub-area where they are located and is also allowed to be changed during the simulation. The obstruction of radio propagation is also implemented in this model, and some of the pre-mentioned conventional models are modified to take into account the environmental effects and to cope with obstacles.

4.3.1 Environment Objects

Different types of sub-areas are abstracted to the Environment Objects (EOs). The EOs can be classified into two categories: Non-Accessible Area (NAA) and Accessible Area (AA). The NAA area represents the restricted area where no movement is allowed inside. The AA area represents some places where mobile nodes can move in and out. An AA can contain Lanes, Paths, Routes, Junctions, NORmal Accessible-Area (NORAA) and Hotspot objects.

Some hierarchical relationships are also given to EOs. For instance, a Route is composed of Paths, Junctions and even NORAAs, A Path can be composed of Lanes, and NORAAs can be a container area for Hotspots. Figure 4.3 illustrates the structure of EOs.

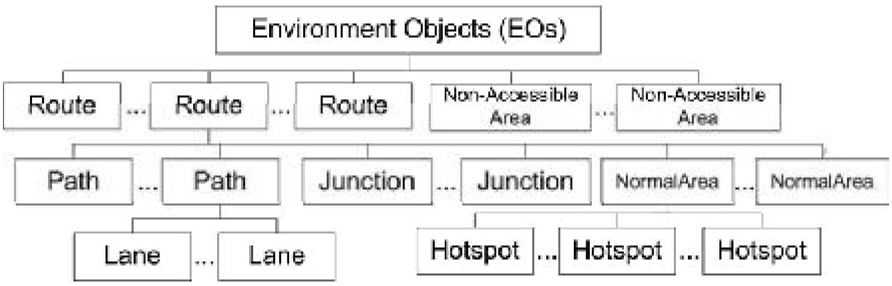


FIGURE 4.3 THE STRUCTURE OF ENVIRONMENT OBJECTS (EOS)

With the introduction of EOs, complex environments can be easily constructed. Each EO is given some intrinsic characterises which have influence on the mobility of the mobile nodes. Typically, the mobile node located in the Lane must follow the Lane to the exit with a maximum speed limit; if a Junction is encountered, a mobile node is forced to choose one of the exits to enter the next adjacent EO. The NORAA is a very flexible EO because it can be used as a container area. If it is a free space area, a mobile node can move using its conventional mobility model. If it contains Hotspots, mobile nodes will be forced to commute among the Hotspots. If it contains a NAA, the accessible space inside it for mobile nodes is reduced. The full description of the EOs is given in Table 4.1.

TABLE 4.1 THE DESCRIPTION OF ENVIRONMENT OBJECTS

Name		Description
Accessible Area (AA)	**NORAA (N)**	If there are no sub-areas located inside the NORAA, the mobile nodes can move freely inside its area; However, a NORAA can contain Hotspot(s) and NAA(s), in which case the behaviors of mobile nodes will be affected and restricted.
	Lane (L)	Entry and Exit must be defined for a Lane. Once the mobile node moves into a Lane from the Entry, the node has to move towards the Exit.
	Path (P)	A Path can consist of one Lane or multiple parallel Lanes. The mobile nodes moving in a Path are not allowed to change its Lane and they must move from the Entry towards the Exit of the Lane where it is located.
	Junction (J)	Junction is used to connect two Paths, or two NORAA, or one Path and one NORAA.
	Route (R)	Route is the resulting EO if the Path, Junction and NORAA are joined together.
	Hotspot (H)	Hotspot is used to represent the attracting area where the mobile nodes may visit frequently.
Non-Accessible Area (NAA)	**NAA**	NAA is the area where no mobile node can move inside. The boundary effect will occur if the mobile node encounters a NAA in the way.

4.3.2 Environment Configuration

It is also assumed in EAM that some of the EOs might have some properties in common. They may have restraints on the speed, the direction and capacity which is the maximum number of mobile nodes the EO can accommodate. Table 4.2 gives the full description of all properties defined in the EAM model and Table 4.3 shows the association of the properties and the EOs.

TABLE 4.2 THE PROPERTIES OF ENVIRONMENT OBJECTS

Properties	Description & Value
MaxSpeed	Description: The maximum speed at which the mobile nodes can move when they are located in this area. Value: The speed in meter/second (m/s). Any speed not less than 0.0m/s. Example: 3.5(m/s)
MaxDirection	Description: The maximum direction in degrees that the mobile nodes can move when they are located in this area. Value: The angle in degrees, ranges from -180.0 to 180.0 degree. Example: 180 (degree)
MinDirection	Description: The minimum direction in degrees that the mobile nodes can move when they are located in this area. Value: The direction in degree ranges from -180.0 to 180.0 degree. Example: -180 (degree)
InboundAreas	Description: InboundAreas are used to specify the entry areas where the mobile nodes can move into this area from. Value: The name of the EO. If more than one area exist, the names of EOs must be separated by '-'. Example: J2-A1
OutboundAreas	Description: OutboundAreas are used to specify the exit areas where the mobile nodes can move into from the area it is located. Value: The name of the EO. If more than one area exist, the names of EOs must be separated by '-'. Example: J1-A2
Capacity	Description: Capacity is the maximum number of mobile nodes the area can accommodate. Value: Any positive integer. Example: 10
MaxDuration	Description: MaxDuration is the maximum duration of time the mobile nodes can stay inside the area. Value: The duration in second (s). Example: 40 (s)
Components	Description: Components are used to specify the sub-areas located inside this configured area, i.e. the areas that it consists of. Value: The name of the EO. If more than one area exist, the names of EOs must be separated by '-'. Example: H1-H2
ClosedArea	Description: ClosedArea is used to indicate if this area is considered as a signal-blocking area. If this is set to be true, its boundaries will be regarded as obstacles. Value: Boolean value, True/False. Example: true
MobilityModel	Description: MobilityModel is used to specify which mobility model the mobile nodes should use once they move into the area. Value: The name of the mobility model. The mobility model can be any one of Random Walk, Random Waypoint, Random Direction, GaussMarkov, Boundless, Hotspot and RPGM. Example: randomwalk

TABLE 4.3 THE ASSOCIATIONS OF THE ENVIRONMENT OBJECTS AND THE PROPERTIES

	NORAA	**NAA**	**Route**	**Path**	**Lane**	**Junction**	**Hotspot**
MaxSpeed	√	X	X	X	√	X	√
MaxDirection	√	X	X	X	X	X	√
MinDirection	√	X	X	X	X	X	√
InboundAreas	√	X	X	X	√	√	√
OutboundAreas	√	X	X	X	√	√	√
Capacity	√	X	X	X	X	X	√
MaxDuration	√	X	X	X	X	X	√
Components	√	X	√	√	X	X	X
ClosedArea	√	√	X	X	X	X	X
MobilityModel	√	X	X	X	X	X	√

√ = the property is applicable to the EO
X = the property is NOT applicable to the EO

4.3.3 Environment-Aware Movement

The EAM can integrate with many Entity Models such as the Random Waypoint model, the Boundless model and Group Models like RPGM, i.e. the mobile nodes can move using conventional mobility models. Since all these models are blind to the environment, they are revised so that the behaviours of the mobile nodes can also be influenced by the properties and characteristics of the environments. Furthermore, the Boundary Effects, *Bouncing* and *Surrounding*, are introduced in EAM and applied to the mobile nodes to enrich their environment-aware capability. For example, different behaviours are designed for the Random Walk model and the Random Waypoint model when a NAA is encountered. The Bouncing behaviour is applied to the Random Walk model. Figure 4.4(a) illustrates the effect: the node bounces to another random direction at boundary *e1*. Compared with the Random Walk model, the Random Waypoint model features a target-driven behaviour so that Bouncing is not applicable. Thus, a different boundary effect called Surrounding is proposed. With *Surrounding* behaviour, once the next destination is determined, the mobile node will try to get there even if there are obstacles blocking the expected path. Figure 4.4(b) illustrates this effect: the node starting at *S* moves towards *D*, it actually travels along the boundaries *e*3-*e*4-*e*1, and then gets to *D*.

Some additional models are also proposed herein in order to cope with some complex environments. These sub-models include: the Route model, the Hotspot model and two City Inter-Vehicle Communication (IVC) models, Bus-aided City IVC model and Roadlamp-aided IVC model. The details of these models are given in Section 4.4.

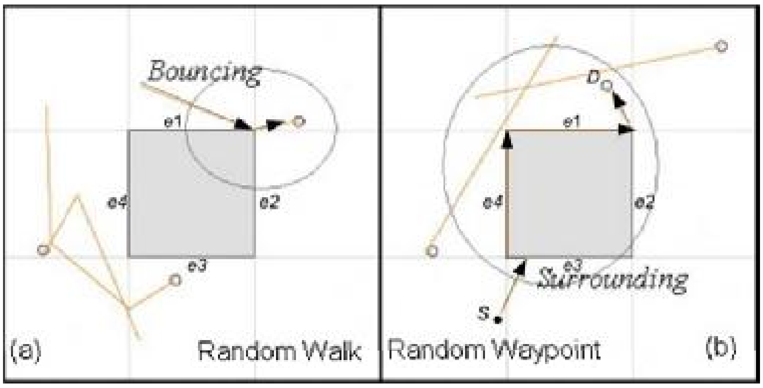


FIGURE 4.4 THE BOUNDARY EFFECTS (BOUNCING AND SURROUNDING B) APPLIED TO DIFFERENT MOBILITY MODELS.

4.3.4 Transmission Obstruction

The radio propagation could be one of the major issues that influence the performance of MANET. The received signal can suffer significant power drop-down due to attenuation, multipath fading, etc. The Two-Ray Pathloss propagation model is used to calculate the power of the received signal. In EAM, the Open Areas and Closed Areas are defined to help the mobile nodes identify which EO should be considered as an obstacle. It is assumed that if there is a boundary of an obstacle geographically located between the LOS range of the pair of mobile nodes, then the signal transmitted from either of them will not reach the other node. Figure 4.5 demonstrates an example of the signal-blocking effect. The dashed lines on the figures indicate the broken links between the nodes because the signal could be blocked by the building and the Non-Accessible Area (NAA).

4.4 THE ENVIRONMENT-AWARE MOBILITY SUB-MODEL

4.4.1 The EAM Sub-models: Hotspot Mobility Model and Route Mobility Model

Two particular realistic environments are modelled and studied. The Hotspot model is proposed to model the movement of the mobile node when attractive places exist in the simulation area. The Route model can be used to construct some complex environments such as a city area. As part of the Environment-Aware Model, some particular environmental factors are also introduced in each model.

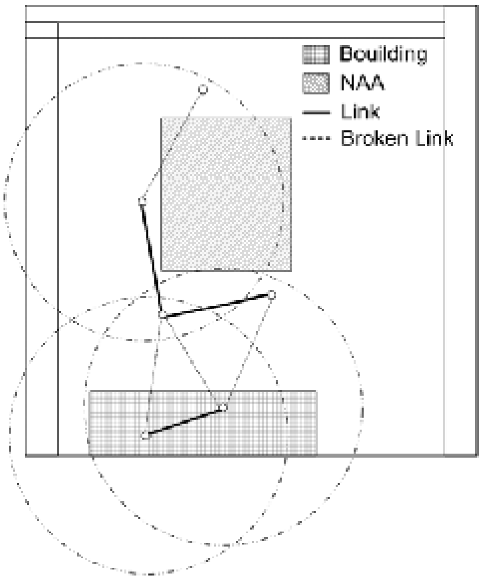


FIGURE 4.5 ILLUSTRATION OF THE SIGNAL-BLOCKING EFFECT

4.4.1.1 Hotspot Mobility Model

The idea of a Hotspot is mentioned in [61] as a future work. In many real world environments, there exist some attraction sub-areas where mobile nodes will frequently visit. In the case of a shopping mall, new shops or on-sale shops obviously will attract more shoppers. Most of the visitors to an art gallery will stay at some famous masterpieces and skim those they feel not interesting enough. It this case, the mobile nodes are moving to some of the hotspots only, which actually reduces the efficient accessible space. This type of deterministic movements is modelled by the Hotspot mobility model. We introduced several intrinsic properties which can be configured for the hotspot. The MaxDuration defines the maximum time a mobile node can stay inside the hotspot. Each hotspot allows a maximum number of mobile nodes that can stay inside at the same time, this number is set by the property Capacity. Once the number of the mobile nodes reaches the Capacity of the area where they located, the mobile nodes have to make an alternative decision. Different behaviours will be used by human in this situation when the target hotspot is found full of visitors. Three strategies are designed and any one of them can be applied to the node:

- In strategy I, the mobile node slows down so that the hotspot can allow at least one more nodes to move in when it arrives at the hotspot. (as shown in Figure 4.6)

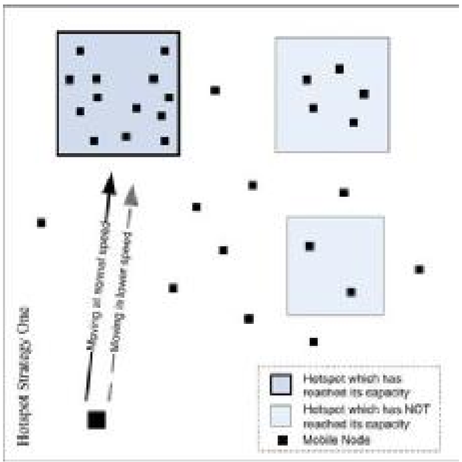


FIGURE 4.6 ILLUSTRATION OF HOTSPOT STRATEGY I

In strategy II, the mobile node moves to a non-hotspot area and uses Random Waypoint mobility model for a while, then tries to head to that hotspot again. This is inspired by the behaviour that a visitor will wander around his favourite hotspot until he sees that some others are leaving that hotspot. (as shown in Figure 4.7)

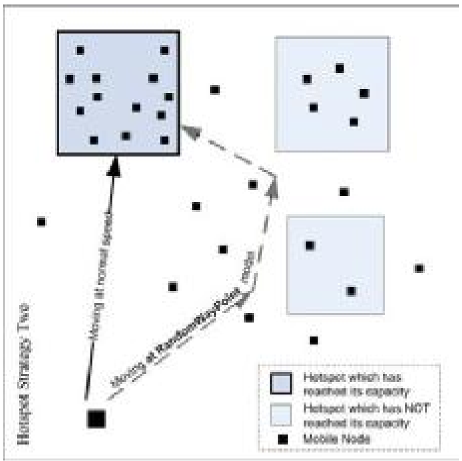


FIGURE 4.7 ILLUSTRAION OF HOTSPOT STRATEGY II

- In strategy III, the mobile node goes to another hotspot in the simulation area. This is inspired by the behaviour that a visitor who is unhappy with waiting and will decides visit next area which interests the most. (as shown in Figure 4.8)

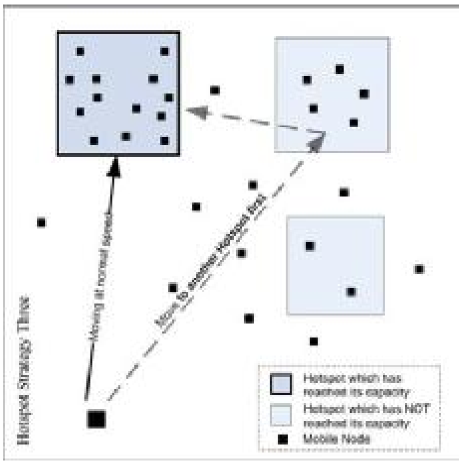


FIGURE 4.8 ILLUSTRATION OF HOTSPOT STRATEGY III

4.4.1.2 Route Mobility Model

The Route mobility model models some complex environments, such as a city area, an urban road traffic. The following are some of the primary features.

A hierarchy structure is used for constructing the route. In order to describe the route in detail. Hierarchy environment objects are defined, which include Lanes, Paths, and Routes. A Path is one segment of a route and composed by one or multiple Lane objects. A Path allows only unidirectional movement. The maximum speed allowed can be different in different Paths. With the integration of these three environment objects, the equivalent environments mentioned by the Pathway model, Manhattan model and Virtual Track model could also be constructed in Route model.

A Route can contain a Junction. A Junction is similar to the Switch Station mentioned in [64], it is a connection point of multiple Routes. When mobile nodes arrive at the Junction, they will randomly choose one of the routes attached to this Junction. In other words, mobile nodes belong to two different groups can join into one group when leave the Junction, and mobile nodes in one group can move towards two directions when leave the Junction. In this way, the group merge and split described in [64] can be simulated.

- Integration with conventional mobility models. This is the key contribution of the Route model in which the Paths can be connected by either Junctions or NORmal Accessible-Areas (NORAA). Once the mobile nodes enter the NORAA, the mobility model that they currently are using could be switched to the one associated to the NORAA. After a certain time (the duration is dependent on the properties, MaxDuration and MinDuration of the NORAA), the nodes will leave the NORAA and randomly choose one of the outbound Paths attached to this NORAA. Furthermore, the Route model can also co-exist with other conventional models so the simulation environments can be simulated in detail as shown in Figure 4.9 for example. The mobile nodes can enter the Computer Science department from the Portobello Street, switch to Random Waypoint mobility model at the speed up to 3m/s, leave the department through the exit to Regent Street and switch back to the Route mobility model again.

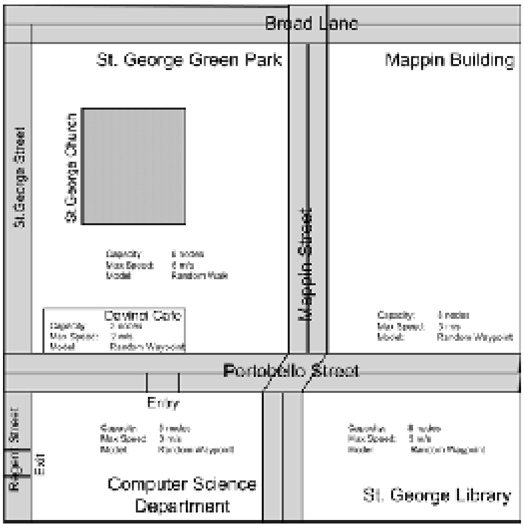


FIGURE 4.9 THE MAPPIN AREA, SHEFFIELD UK CONSTRUCTED BY ROUTE MOBILITY MODEL

4.4.2 The City Inter-Vehicle Communication (IVC) Systems with EAM

The Inter-Vehicle Communication (IVC) networks are regarded as a new type of MANET system. The city is the typical environment where the IVC networks are usually deployed. The city IVC environment is studied in this section, two particular systems, Bus-aided IVC network and Roadlamp-aided IVC network are introduced by taking account of Buses and Road lamps, respectively.

4.4.2.1 The Node Heterogeneity in The City IVC Environment

In the IVC system which exists in the city environment, the mobile nodes consist of all sorts of vehicles with different characteristics of movement. To better understand the environment, mobile nodes are classified into five categories: High Mobility Node, Low Mobility Node, Restricted Nodes, Bus Node, and Static Node. The description of each category is given in the following:

- A **High Mobility Node (HMN)** is the most common node existing in IVC networks in a City environment. The nodes belonging to this category normally have relatively higher range of speed compared to other nodes. Another important characteristic that should be noticed is that all the HMNs have certain randomness. Every node moves towards a random destination through one of the available routes; each node can have a different random speed, but they must have more or less the same average speed and this depends on the traffic load. One typical High Mobility Node is a car.
- A **Low Mobility Node (LMN)** has the same level of randomness as a HMN, but they usually move with a much slower speed. A typical example of this category is a pedestrian.
- A **Restricted Node (RN)** is located inside certain obstacles such as a building, a stadium and so on. The nodes belonging to this category normally exhibit the lowest speeds inside a relatively small sub-area of the environment. The HMN and LMN move into a restricted area, they are reclassified as the Restricted Nodes. A visitor to an Art Gallery, for example, can be considered as a good representative of this category.
- A **Bus Node (BN)** is defined to represent a mobile node such as a bus or a supertram. The nodes belonging to this category normally have a speed between that of a Low Mobility Node and a High Mobility Node, but more importantly, the node's average speed is relatively constant in order to catch up with its timetables and it is normally moving in a pre-defined route and pauses for a certain time at some locations along the route, e.g. bus stops.
- A **Static Node (SN)** is defined to represent the nodes which are not moving during the observation period. The speed of a Static Node is considered as 0m/s. The traffic lights located at the junctions and the roadlamps located along the routes can be treated as typical examples, assuming they are equipped with radio transceivers.

All the five types of mobile nodes can be modelled and exist in the same simulation period. The Bus Node is normally used to model the behaviour of the Bus. During the simulation period, the number of buses is kept constant, and different pre-defined routes are assigned to each bus node. All the bus nodes moving along the same route can be given the same speed, and the speed assigned to the nodes moving along different routes could be different. The bus routes are allowed to have some segments overlapped. Figure 4.10 illustrates two partial overlapped routes in a city environment.

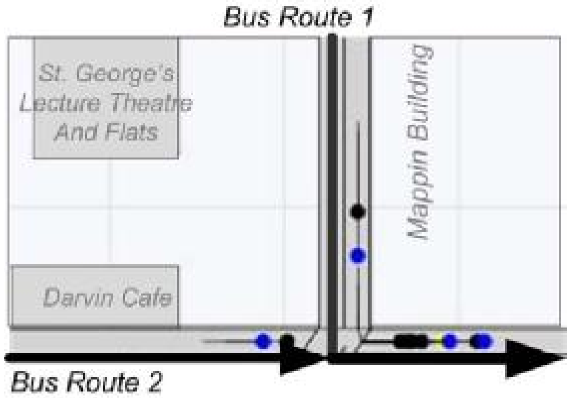


FIGURE 4.10 ILLUSTRATION OF TWO PARTIAL OVERLAPPED ROUTES

4.4.2.2 The Description of The Bus-aided IVC Network

The regular nodes such as the buses and the trams normally have pre-defined routes to travel and they all should follow a time table as much as they can. A bus is considered to be the most important facility for the transportation in some modern cities where the special lanes are allocated only for the buses. With these advantages, the bus nodes are assumed not to be affected by traffic jams. Therefore, the BNs herein are assumed to travel at a constant speed along the pre-defined route. Figure 4.11 gives the illustration of two bus routes. The idea of taking the advantage of the regular movement of the bus is first considered in BusNet [80]. With antenna-equipped BNs, the other nodes which are physically out of communication range can be re-connected. The average lifetime of the links maintained by the regular nodes is expected to be longer in some situations since the BNs are moving together with other types of nodes.

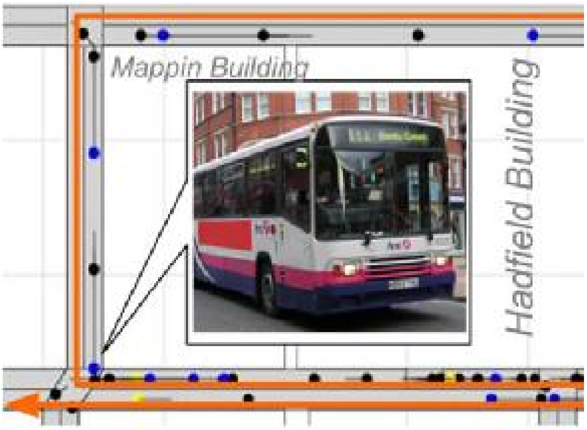


FIGURE 4.11 ILLUSTRATION OF TWO BUS ROUTES

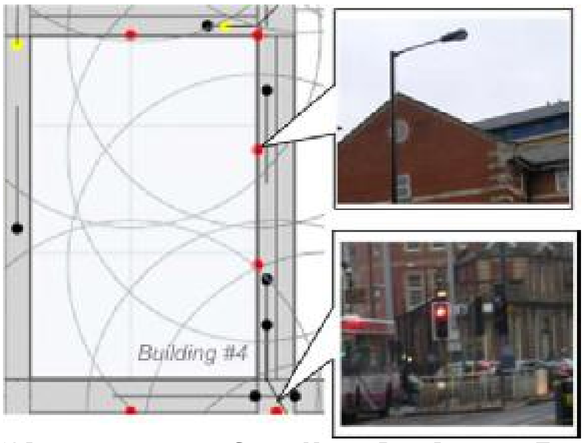


FIGURE 4.12 ILLUSTRATION OF THE STATIC NODES: ROADLAMP AND TRAFFIC LIGHT

4.4.2.3 The Description of The RoadLamp-aided IVC Network

Along the main streets in the city environment and the highways, roadlamps can normally be found at certain distance apart, as shown in Figure 4.12. Inspired by the idea of the Access Point in the WiFi networks, it is assumed that some of the roadlamps can be equipped with wireless transponder and serve as access points. The overall network performance is expected to be improved with the increment of network connectivity. Traffic lights are normally located at the junctions. Ideally, the transmission range of the antenna installed on the traffic light can partially cover both the inbound and outbound lanes. Therefore, the problem illustrated in Figure 4.1 is expected to be solved. Both the roadlamps and the traffic lights are assumed not to be involved in traffic initialization and termination, i.e. they only function as intermediate nodes. The RoadLamp-aided City-IVC network is expected to have more stable network connectivity than bus-aided City-IVC network; however there is again a trade-off herein. Frequent congestion can occur due to some unnecessary packets forwarded by these nodes if too many of them are introduced to the network.

4.5 CONCLUSIONS

With the understanding of the influence on the performance of networks by the mobility of mobile nodes, the need to develop a framework for better study the mobile ad hoc networks is identified. In the framework, a new mobility model with the awareness of the environment became a key work.

This chapter has introduced a new mobility model called the Environment-Aware Mobility (EAM) model which can be used to simulate the mobile ad hoc network. This mobility model differs from other conventional models in that it examines the simulation environment and takes into account the characteristics of various environment objects. In EAM, conventional mobility models can co-exists in different area of the environment, and the mobility of mobile nodes is influenced by the environment.

The EAM is designed to be a very generic. In order to easily construct and configure the environment, some necessary features are developed in this model. For example, basic environment objects such as Route, Hotspot, Non-Access Area and Normal Are and so on are introduced and each environment object is associated with some properties such as capacity, mobility model etc. The expandability is also carefully considered in EAM model so additional features such as building a new mobility model can be easily implemented, which is described in detail in section 5.3.3.

In order to better demonstrate the features of EAM model, two sub-models based on EAM were developed to address some special situation. The Hotspot model is used to simulate the environment where attractions exist, and the Route model can be used to construct certain environments such as city areas. With the realistic factors concerned, more reasonable simulation results can be obtained and better understanding of the performance of the mobile ad hoc network can be achieved.

The EAM model also facilitates the study of some particular communication systems, such as City Inter-Vehicle Communication (IVC) system. The characteristics of different mobile nodes in the IVC system are studied, and by taking the advantage of two special nodes, Bus and RoadLamp nodes, the network performance can be enhanced.

A set of tools are also developed in this environment-aware framework for the implementation of the EAM model and simulation of mobile ad hoc networks, and it will be detailed in Chapter 5. All the simulation results are presented in Chapter 6.

Chapter 5: MOBILITY-CONCERNED SIMULATION IN THE ENVIRONMENT-AWARE FRAMEWORK

5.1 INTRODUCTION

In mobile ad hoc networks, many mobility models have been proposed to model complex scenarios. Using these mobility models, more valuable information of self-organized networks can be studied. Although there are a few research tools, especially network simulators developed and used for the study of protocols (MAC protocols, Routing protocols, etc), they lack the ability to model the mobility of mobile nodes.

In Chapter 4, the environment factors were introduced into the mobility model. The performance analysis of a network can be expected more reasonable with the integration of these environment factors with conventional models. However, none of existing tools can be used to build the required simulation environment. In this environment-aware framework, a set of tools for environment-concerned simulation is developed. This framework can be used for the network simulation, and it can also help with the visualization of the movement of mobile nodes in the simulation. Several performance evaluation tools have also been developed in this framework to measure both connectivity-related metrics and routing-related metrics in the mobility-concerned environment.

This chapter details the structure and usage of the tools included in the framework and the approaches used.

5.2 FEATURES REQUIRED

In this section, the features required for this framework are described in detail.

5.2.1 Environment Construction

In Chapter 4, a novel mobility model named Environment-Aware Mobility (EAM) was introduced. The environment where a MANET is deployed is introduced into EAM model. The environments are represented by some environment objects, such as a Route, a Junction, an Accessible Area, and a Hotspot etc. These environment objects are essential to this model. Thus, in addition to developing a mobility simulator the environment objects must be properly modelled and a tool is required to utilize these environment objects in order to represent a complex realistic environment. The environment constructed can be read by the mobility simulator and has effect on the mobility of mobile nodes during the simulation.

5.2.2 Mobility Visualisation

Very few simulators have a good tool which can represent the mobility visually, i.e. even though the mobility of the mobile nodes has been accepted as a very important factor in MANET, the current tools do not enable the users to see how the mobile nodes move. A new tool has been developed in order to help researchers better construct the simulation environment and easily verify the simulation result against the mobility and the environment, a new approach is required to visually draw and represent the environment and also monitor the movements of the mobile nodes.

5.2.3 Expandable Generic Model

One feature of EAM is that the mobility model can be switched from a conventional model to another one when the mobile node moves into a particular area. In other words, the conventional mobility models must be environment-aware in EAM. Therefore the EAM model should be compatible with other conventional models, which means:

The EAM model can be integrated with other models; the models will have the same movement behaviours but will be environment-aware;

There are many models proposed for MANET networks. It is impossible to integrate all the existing models into the EAM model, but EAM could be expandable to include any existing model.

5.2.4 Measurement

In order to verify the impact of mobility on the performance of a mobile ad hoc network, some metrics need to be measured. Two types of metrics are used. The connectivity-related metrics are used to measure the mobility level of the network; the routing-related metrics are used to examine the performance of the routing protocol which the network is using for data transmission. In this framework, a set of tools to measure these metrics are expected to be developed.

5.3 MOBILITY-CONCERNED SIMULATION

5.3.1 Overview of Scalable Vector Graphic (SVG)

This framework makes extensive use of a graphic standard called Scalable Vector Graphics (SVG). The full specification can be found in W3C [53]. Because of the importance of SVG, its overview of SVG is given here.

SVG is an eXtensible Markup Language (XML) based grammar used to render two-dimensional rich, interactive, and powerful graphics as well as multi-media applications. Unlike the raster images (pixels/dots) that get all distorted and fuzzy when they are stretched. A browser can easily render an SVG image in any size (Scalable) in good quality. SVG also contains not the image itself (dots) but rather a set of readable XML elements than can be understood by the browsers (with SVG plug-in installed) and other SVG viewers. These clients actually draw the vectors (lines) to comprise the image.

By being written in XML which is extremely popular and reliable for structured information exchange, SVG has been used in a wide range of contexts. Some of the common applications include web graphics, online maps, graphical user interface for web-based application and charting other data visualization. With the growing usage of SVG, the latest graphic tools such as MS Visio all offer the option to save the current file in SVG format, which makes drawing a SVG graphic rather easy. SVG are also supported by more and more devices such as mobile phones. The latest mobile handsets have support for a mobile SVG profile, for instance SVG Tiny 1.2.

SVG drawing can be interactive and dynamic. In order to draw a complex graph, SVG contains a set of basic shape elements including rectangles, circles, ellipses, lines, polylines and polygons. Mathematically these shape elements are equivalent to a general path element which can be used to represent any arbitrary shape. Each element is associated with a set of attributes which provides the detailed information (such as the coordinates, the colours etc) for rendering the shape. List 5.1 shows a simple SVG file where a rectangle is defined filled with light blue and with a navy border. Figure 5.1 shows how it looks like when rendered in a SVG viewer.

```
<?xml version="1.0" standalone="no"?>
<!DOCTYPE svg PUBLIC "-//W3C//DTD SVG 1.1//EN"
"http://www.w3.org/Graphics/SVG/1.1/DTD/svg11.dtd">
<svg width="12cm" height="4cm" viewBox="0 0 1200 400"
xmlns="http://www.w3.org/2000/svg" version="1.1">
  <desc>Example rect01 - rectangle with sharp corners</desc>
  <rect x="400" y="100" width="400" height="200" fill="lightblue"
stroke="navy" stroke-width="2"  />
</svg>
```

LIST 5.1 A SIMPLE SVG FILE WHERE A RECTANGLE IS DEFINED FILLED WITH LIGHBLUE COLOR AND STOKED WITH NAVY

FIGURE 5.1 AN EXAMPLE OF A RECTANGLE RENDERED IN SVG

SVG supports the ability to change vector graphics over time, i.e. it allows animation. The SVG content can be animated by Using SVG's animation elements. SVG document fragments can describe time-based modifications to the document's elements. With various animation elements such as *animate*, *animateMotion*, *animateColor* and *animateTransform*, the motion paths and some effects like fade-in or fade-out, and objects that grow, shrink, spin or change colour can be defined.

Some of these outstanding features of SVG are adopted in our work and used as the key approaches for the environment construction and mobility visualisation in our mobility-concerned simulation.

5.3.2 Overview of The Environment-Aware Framework

All the environment objects are designed with SVG technology in this framework. The layout of all the environment objects is described in a SVG file (Environment Layout File). The relationships between sub-areas and various properties of each sub-area are given by a text-formatted configuration file (Environment Configuration File). A SVG file is generated after the simulation is finished. This animation-supported SVG file can be very useful for researchers to explicitly observe the movements in the simulated scenario. The details produced in this SVG file can be configured by the users by modifying a text-formatted configuration file (Output Configuration File). When the simulation starts, a scenario generator reads all three files to become aware of where the environment objects are and their properties. The mobile nodes are distributed into the accessible sub-areas. The mobility factors such as speed, direction and the mobility model attached to each node are determined by the properties of the areas in which they are located. The ns2 simulator introduced in section 2.3 is used in this framework for the simulation of routing protocols. All the movements are recorded and converted to a ns2 compatible movement scenario file upon the end of the simulation. ns2 is also modified in order to be able to read an Obstacle Description File to affect radio signal. Figure 5.2 illustrates this framework which shows the tools to be described in rest of this chapter together with the EAM model.

5.3.3 Environment-Aware Mobility Modeller

In this section, the mobility modeller for Environment-Aware Mobility (EAM) model is described in detail.

5.3.3.1 The Mobility of Mobile Nodes

Some key mobility factors such as speed, direction etc need be carefully modelled in order to track the movement of mobile nodes.

Mobility factors

In the Environment-Aware Mobility (EAM) mobility model, every mobile node is assigned a location with the coordinates (x, y, z). Since most of the currently research only focus on the 2-D environment, the z-axis is set to 0 by default to be compatible with other network simulators such as ns2.

A number of typical mobility models have been studied in Chapter 4 where the EAM model is introduced, which helped to understand the factors related to the mobility of mobile nodes. In general, every mobile node in the network should have its own movement pattern, i.e. it makes the decision to move at a certain speed, towards a direction and possibly at certain acceleration. However, in some situation, the mobile nodes are grouped together and show group behaviour. In those cases, the movements of mobile nodes are relevant to each other, i.e. they have individual movement, but the movement is inevitably effected by the group's mobility decision. A good example is when a group of tourists visit a famous city. They will slow down when they find something that interests them, but they will also speed up in order to catch up the head of the group, e.g. the tourist guide.

Individual mobility, i.e. Entity Mobility and Group Mobility are carefully considered and modelled with different mobility factors in this thesis. Every mobile node is assigned an entity velocity (entity direction and entity speed) and group velocity (group direction and group speed). Both velocities are stored into an object called MobileNodeVelocity. Note that, the velocity here can be either defined by the direction in degree and the speed at that direction (meters per second), or by the speeds at the x and y axis and both speeds can be assigned a negative value to reflect the direction.

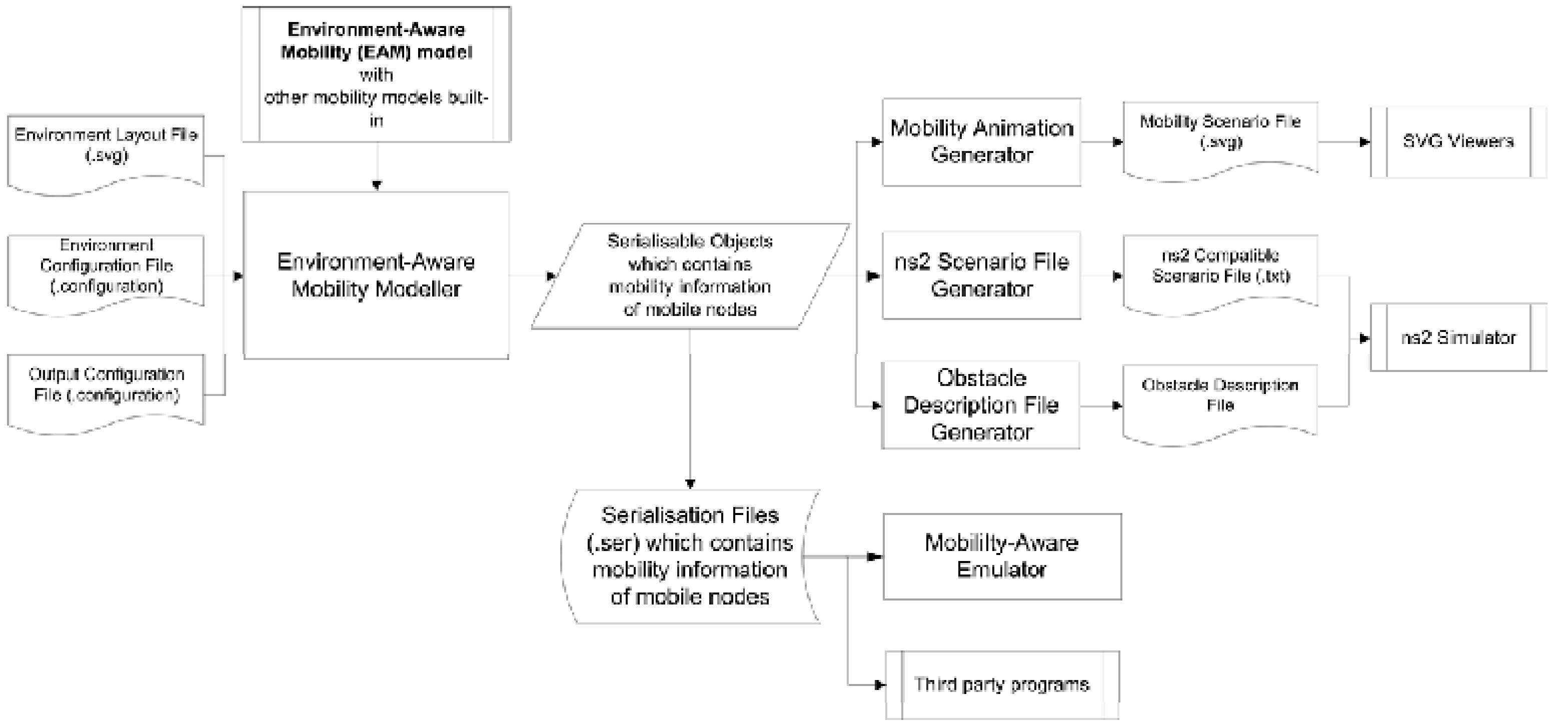


FIGURE 5.2 OVERVIEW OF THE ENVIRONMENT-AWARE FRAMEWORK FOR MOBILITY-CONCERNED SIMULATION.

The status of the mobile node, including the MobileNodeLocation and the MobileNodeVelocity are wrapped together into the object MobileNodeStatus which is attached to every mobile node simulated. The values of the properties in MobileNodeStatus are assigned when the mobile node is initiated at the beginning of the simulation. Figure 5.3 shows the relationship between these objects.

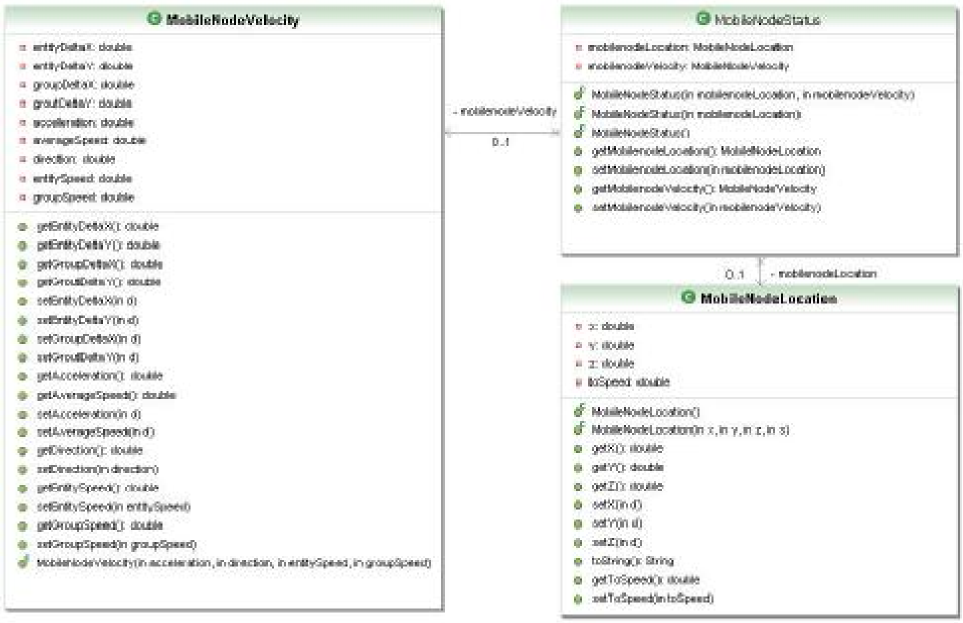


FIGURE 5.3 THE RELATIONSHIP BETWEEN THE OBJECTS, MOBILENODEVELOCITY, MOBILENODESTATUS AND MOBILENODELOCATION

Tracking the movement: Movement Segments

The movement of the nodes is calculated as a sequence of movement segments in every mobility model. The object MNMovementSegment is used for recording each movement segment; it contains the start location, stop location, start time, duration in each segment etc. Depending on the model and its parameters, a movement segment might last for seconds or be very short, and its trace might be a long line or a tiny part of a curve if the node is moving along a path in a circle.

Most of the movement patterns in the mobility models can be segmented into a certain amount of linear movements. Staring from a position (x_{from}, y_{from}) at time t_{start}, the linear movement could take t_{dur} seconds until the mobile node arrives at the destination (x_{to}, y_{to}). A normal behaviour of the mobile node is that it might take a break (pause) at the new location before it starts next movement at t_{new_start}. The MNMovementSegment dose not directly contain the information of the pause time, but it can be calculated by $(t_{new\_start} - t_{start} - t_{dur})$ whenever this is required.

The MNMovementSegment objects are generated as soon as the mobility model gets the next MovementProperties object (i.e. the value of the MovementLocation and MovementVelocity objects). Once the simulation is finished, all the movement segments related to a node are grouped together into an object name MovingPath, i.e. the MovingPath object contains the complete information of the movement of a particular node.

Figure 5.4 shows the Unified Modeling Language (UML) diagram of the objects MNMovementSegment and MovingPath.

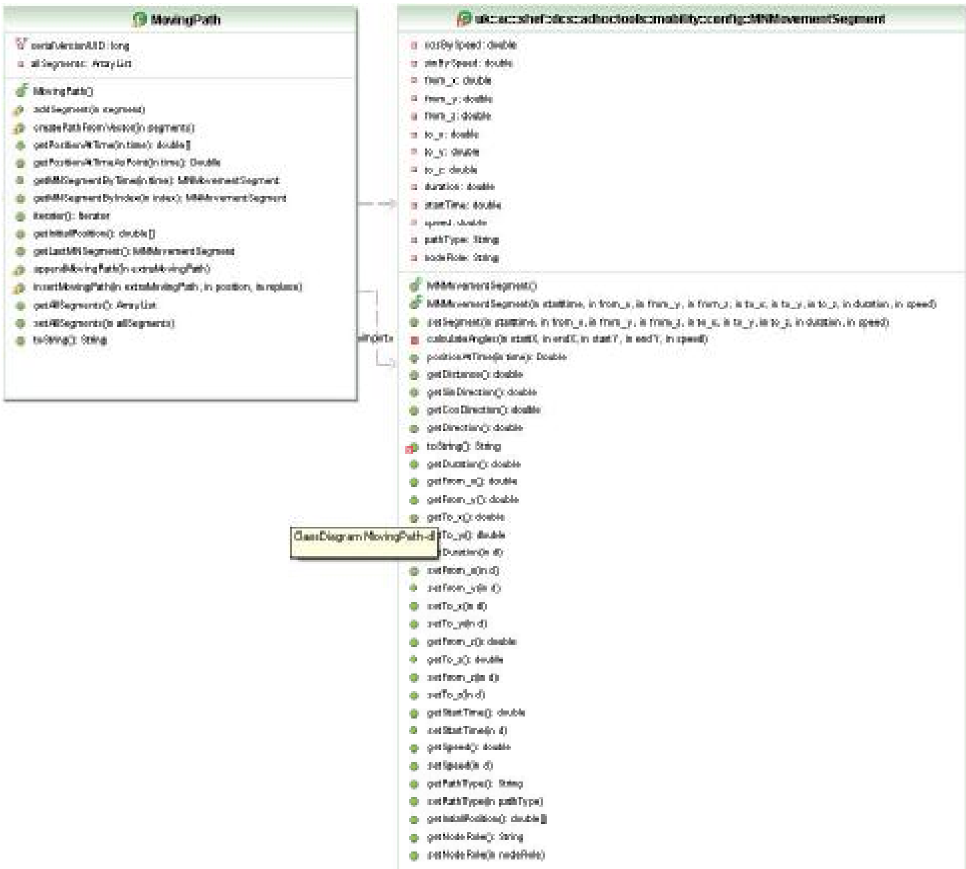


FIGURE 5.4 THE UML DIAGRAM OF THE OBJECTS: MNMOVEMENTSEGMENT AND MOVINGPATH

The Serialization of MNMovementSegment and MovingPath objects

The two objects MNMovementSegment and MovingPath are very important objects in this mobility modeller since the complete behaviour and the mobility parameters at a specific time of any node can be obtained through them.

Both objects are produced during the runtime of the simulation so that their values can be accessed by other objects of the mobility modeller. In order to be able to re-use the complete information of the movement offline in our mobility-concerned simulation framework, these two objects are also designed to be serializable.

In the context of computer science, Serialization is the process of saving an object onto a storage medium (such as a file or a memory buffer) or to transmit it across a network connection link in binary form. The series of bytes or the format can be used to re-create an object that is identical in its internal state to the original object (actually a clone) [81]. In each simulation, the MNMovementSegment and MovingPath objects are serialized into several .ser files in the operating system. Each serialised file represents the objects in binary form, i.e. the full path of a mobile node. By this way, the MovingPath objects are able to be accessed for further study even though the simulations have finished. The process of retrieving the mobility information from these .ser files is called deserialisation which is used in some other modules, e.g. Movement Visualisation, Metrics Evaluation etc. The details of each of these modules are introduced in later sections.

5.3.3.2 The Generic Model

As mentioned in the section 5.2, this mobility modeller is designed to be as expandable as possible in order to deal with all of the different mobility models proposed by other works. As a core part of this modeller, a generic model is designed in order to standardise the process of mobility modelling.

The properties related to a mobility model

Having carefully examined existing mobility models, the common and essential properties of these models have been adopted into the GenericMovementModel as shown in Figure 5.5.

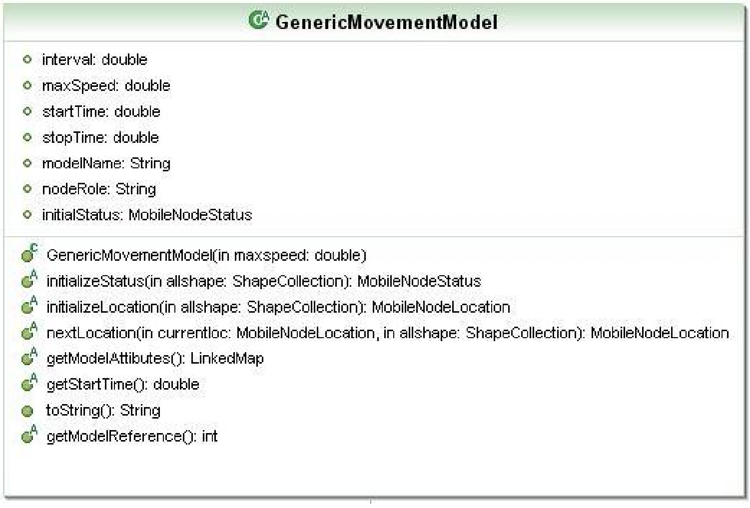


FIGURE 5.5 THE UML DIAGRAM OF THE OBJECT: GENERICMOVEMENTMODEL

These properties include:

- **modelName –** the name of the model.
- **maxSpeed** – the maximum speed of the mobile node. The minimum speed is not included in the generic model since it is not normally used in some models such as the GaussMarkov model.
- **startTime** – the time the mobile node actually starts the movement in the simulation. The entire simulation starts at 0 second, but there might be some slight difference for each node to start moving around.
- **stopTime** – the time when the simulation ends, i.e. all mobile nodes are supposed to stop moving at the stopTime.
- **interval** – the duration between two continuous movement epochs. The interval could last for a few seconds in the the RandomWayPoint model or equal to zero which means the nodes are moving continuously as in the GaussMarkov model.
- **nodeRole** – in Chapter 4, the node heterogeneity has been introduced into the the Environment-Aware Mobility (EAM) model. The nodes might play different roles in the scenario simulated, such as a bus or a pedestrian etc. The property nodeRole is used to indicate its role explicitly.
- **initialStatus** – contains the mobility information of the mobile node at the beginning, including the initial location and initial moving speed and direction.

Predefined mobility models

The GenericMovementModel is an abstract Java class, and all the mobility models defined in this modeller must implement this class. A number of mobility models have been developed for the research, including the conventional Random Waypoint mobility model, Random Walk mobility model, Random Direction mobility model, Boundless mobility model, GaussMarkov mobility model, Static mobility model, the group model RPGM mobility model and the EAM model with its two variant models the Hotspot mobility model and the Route mobility model. All these models have been detailed in previous chapters of this thesis. Although they compute the movements using a different algorithm, they all have common properties, as described in previous section.

Initialisation of the mobility model

Every mobile node simulated must be associated with a mobility model which defines its movement pattern. The value of the property initialStatus as shown in Figure 5.5 includes the location, speed and moving direction of the mobile node and this must be initialised at the very beginning of the simulation. In the conventional mobility model, the initial location could be anywhere within the simulation area, the initial speed is normally determined directly or in-directly by the maxSpeed and the algorithm of the mobility model itself, and the direction is determined by the boundaries of the simulation area and the node's current location.

Verification of the location

However, having introduced environment objects into this modeller, the computing of the initial status is far more complicated than the conventional way. The candidate location is the temporary location calculated by the algorithm defined by the conventional model, and this candidate location must be verified against the environment where the mobile node is currently located. This second step is called location verification. If the location verification fails (for instance, the candidate location is found to be located inside a Non-Accessible Area), the calculation of the candidate location will be repeated.

The Model Dispatcher in the EAM mobility model

When the Route mobility model was introduced in Chapter 4, it was indicated that the Route defined in the model can also contains some sections of other environment objects such as NORmal Accessible Area. This means the EAM mobility model can allow for the co-existence of several different models. Once the next location is verified, whether the mobility model should be switched to another has to be decided. If the mobility model permitted in the area where the next location is different from the current mobility model that the mobile node is using, the EAM mobility model will call its Model Dispatcher to get a relevant model to handle the location calculation for the next set of movements.

The expandability of the modeller

Although several typical mobility models have been pre-integrated into this modeller, as mentioned in Chapter 4, many more good models have been proposed for mobile ad hoc networks and more will be developed in the future. It is impossible to integrate them all in this work, but fortunately the design of the Generic Model provides the capability for other researchers to use their models in this framework or to upgrade a conventional model to be environment aware. A new mobility model only needs to overload two methods in the GenericMovementModel, initializeStatus() and nextLocation() to implement its own algorithm for the location calculation, and to register itself with the Model Dispatcher.

5.3.3.3 Environment Objects

In Chapter 4 where the Environment-Aware Mobility (EAM) model is discussed, the Environment Objects are introduced to present diverse areas in the real environment. These Environment Objects include Lanes, Paths, Routes, Junctions, NORmal Accessible-Area (NORAA) and Hotspots. In this section, how these objects are actually implemented into this framework is detailed.

Reading Environment-Layout SVG file

As mentioned before, the SVG contains a set of basic shape elements such as rectangles, circles, ellipses, lines, polylines and so on. On the Environment-Layout SVG file, the Environment Objects of the EAM model are presented by these basic shapes. So in this mobility modeller of the framework, one of the most important task is to read the SVG file and transform the basic SVG shapes into proper objects which can be handled by the modeller.

At the initialisation stage of the simulation, every Environment Object defined in the SVG file is parsed and transformed into a Java basic shape. This shape is simplified into a Rectangle or a Polygon or an Ellipse, each of them is represented by the Rect, Polygon and Ellipse object respectively. These three shapes are the children classes of an Abstract class named AbShape which contains some common properties such as the shapeId, a unique identity assigned to every shape. Figure 5.6 shows their inheritance relationship.

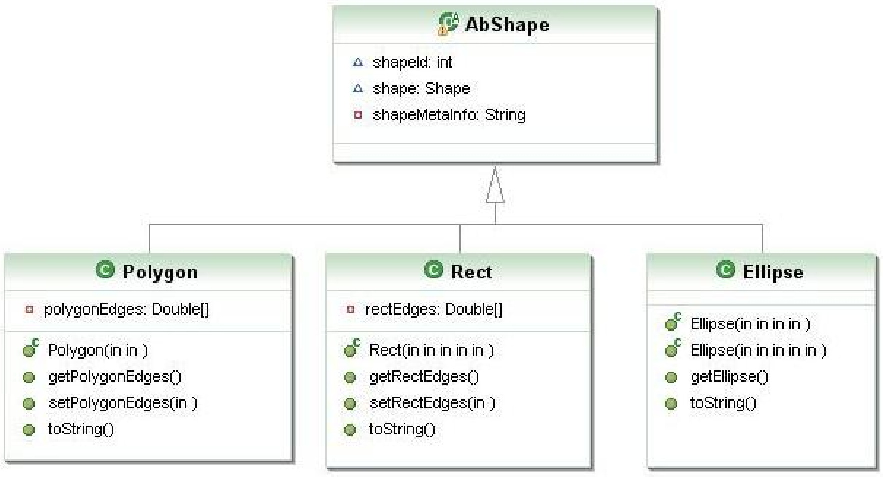


FIGURE 5.6 THE INHERITANCE RELATIONSHIP OF THE OBJECTS: ABSHAPE, POLYGON, RECT AND ELLIPSE

Mapping Environment Objects to Java Objects

In SVG, the SVG basic shapes are used to construct all sorts of environment objects. Since the SVG basic shapes are transformed to the AbShapes, a corresponding Java object is initialised for every environment object defined by SVG. In other words, the environment objects are mapped to Java objects. Six Java objects, including Lane, Path, Route, Junction, Hotspot and NormalAccessibleArea are developed to handle the environment object Lanes, Paths, Routes, Junctions, Hotspots and NORmal Accessible-Area respectively. Figure 5.7 illustrates the mapping.

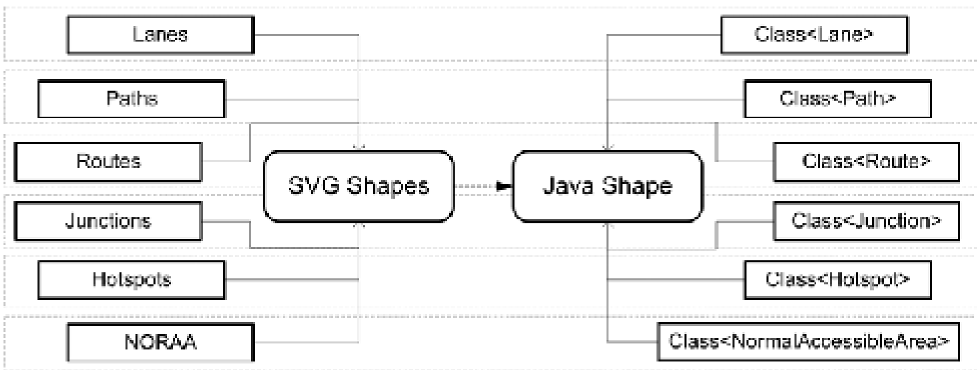


FIGURE 5.7 ILLUSTRATION OF MAPPING ENVIRONMENT OBJECTS TO JAVA OBJECTS

In order to map the structure of the Environment Objects described in Section 4.3, each object is associated with several properties to store the information of the relationships with other objects. For example, it has been stated before that a Route is composed of Paths, Junctions and even NORAAs, A Path can be composed of Lanes, and NORAAs can be a container area for Hotspots. So here the Route object contains a ArrayList of paths, the Path object contains a ArrayList of Lane; The NormalAccessibleArea object has a property named componentList which is used to store the information of the Hotspots which are located inside.

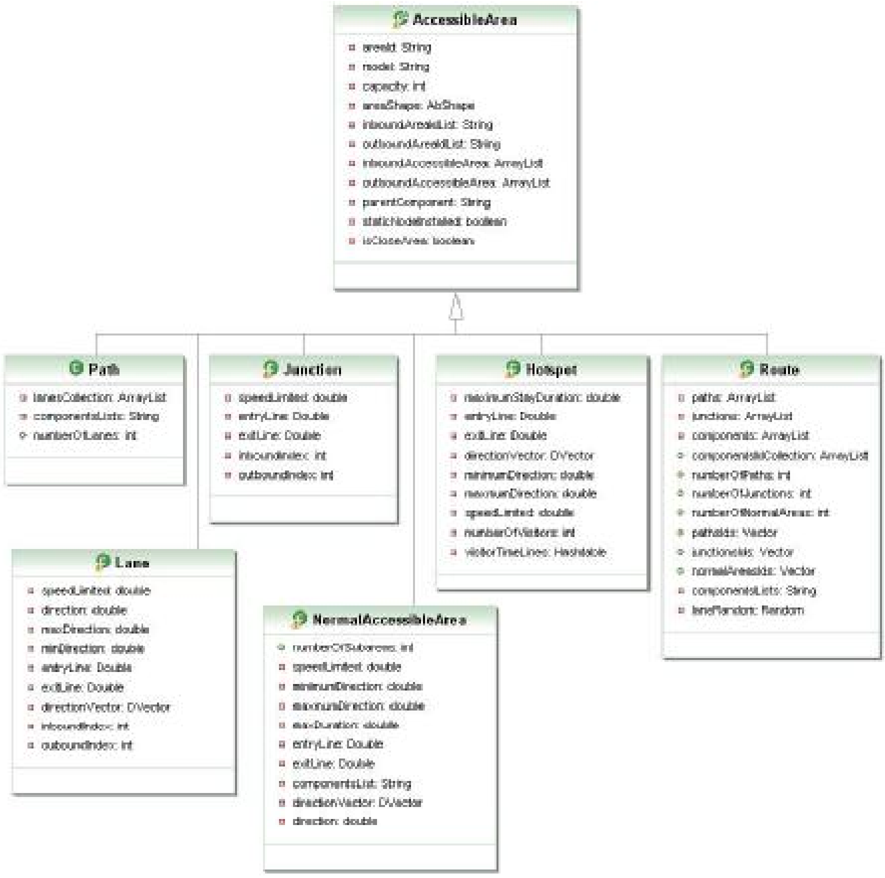


FIGURE 5.8 THE UML DIALGRAM OF THE ENVIRONMENT OBJECTS

Furthermore, the properties of the Environment Objects detailed in Table 4.2 are implemented as the properties of the corresponding Java objects, and the value of each property is read from a file called the Environment Configuration File which is discussed in a later section. Figure 5.8 shows more details about these Java objects in a UML diagram. Note that each of these classes extends to class AccessibleArea which contains some common properties, such as the areaShape in type of `AbShape` which indicates the actual Java shape by which this environment object is presented.

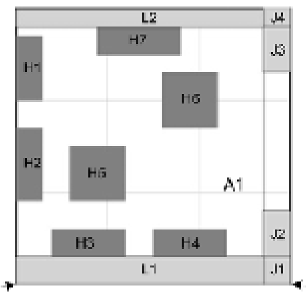
5.3.3.4 The Configuration Files

Three configuration files, Environment Layout File, Environment Configuration File and Obstacle Description File are described in this section in detail. The Output Configuration File will be introduced in section 5.3.5 where the Mobility Visualisation is detailed.

Environment Layout File

SVG contains a set of basic shape elements, such as the rectangle, circle, line, and polygon, these elements are used to represent the environment objects in arbitrary shapes. A typical snippet of an SVG Environment Layout File (ELF) is shown in Figure 5.9.

Note that every Environment Object is identified by the ID of the SVG shape element. A simple convention is set: the ID must start with AA (for Accessible Area) or NAA (for Non-Accessible Area) then followed by an underscore then its *name* which is composed by the object's type plus the index. For example, if an element has an ID of "AA_L1" ('L1' is the name of this object), it means the sub-area represented by this element is an accessible Lane with index 1.




```
<rect id="AA_A1" x="1" y="20" width="270" height="250" fill="none" stroke="black" stroke-width="1"/>
<rect id="AA_H1" x="1" y="30" width="30" height="70"   fill="grey"/>
<rect id="AA_H2" x="1" y="130" width="30" height="80"  fill="grey"/>
<rect id="AA_H3" x="40" y="240" width="80" height="30" fill="grey"/>
<rect id="AA_H4" x="150" y="240" width="80" height="30" fill="grey"/>
<rect id="AA_H5" x="60" y="150" width="60" height="60"  fill="grey"/>
<rect id="AA_H6" x="160" y="70" width="60" height="60"  fill="grey"/>
<rect id="AA_H7" x="90" y="21" width="90" height="30"   fill="grey"/>
<rect id="AA_J1" x="270" y="270" width="30" height="30" fill="lightgrey" stroke="black" stroke-width="1"/>
<rect id="AA_J2" x="270" y="220" width="30" height="50" fill="lightgrey" stroke="black" stroke-width="1"/>
<rect id="AA_J3" x="270" y="20" width="30" height="50"  fill="lightgrey" stroke="black" stroke-width="1"/>
<rect id="AA_J4" x="270" y="1" width="30" height="20"   fill="lightgrey" stroke="black" stroke-width="1"/>
<rect id="AA_L1" x="1" y="270" width="270" height="30"  fill="lightgrey" stroke="black" stroke-width="1"/>
<rect id="AA_L2" x="1" y="1" width="270" height="20"    fill="lightgrey" stroke="black" stroke-width="1"/>
```

FIGURE 5.9 AN EXAMPLE SNIPPET OF ENVIRONMENT LAYOUT FILE (ELF) AND THE DEMONSTRATION OF THE ENVIRONMENT IT PRESENTED.

Environment Configuration File

The SVG layout file provides the model with the location of each EO and helps identify their types. The relationships among EOs mentioned along with their properties are configured in a text-format Environment Configuration File (ECF). It is also assumed in EAM that some of the EOs might have some properties in common. They may have restraints on the speed, the direction and capacity which is the maximum number of mobile nodes the EO can accommodate. The full description of all properties and the association of the properties and the EOs have been described in Chapter 4.

All these properties are configurable in the ECF. As an example, a typical configuration for the Normal-Accessible Area with ID=AA_A1 which exists in the environment of Figure 5.9 is given in List 5.2. It can be derived that the area A1 which is adjacent to Junction J2 which is its entry area. A1 can be considered as a room since it is set to be a CloseArea, it contains three Hotspots (H1, H2 and H3) and a maximum of 10 mobile nodes are allowed to stay in at the same time. As for the mobility factors, the mobile nodes located inside can move in any direction but with speed up to 7m/s, and the general movements are modelled using the Hotspot Model.

```
adhoctools.mapconfig.normalarea.details.area1.id          = A1
adhoctools.mapconfig.normalarea.details.area1.maxspeed     = 7.0
adhoctools.mapconfig.normalarea.details.area1.maxdirection = 180.0
adhoctools.mapconfig.normalarea.details.area1.mindirection = -180.0
adhoctools.mapconfig.normalarea.details.area1.inboundareas = J2
adhoctools.mapconfig.normalarea.details.area1.outboundareas= J3
adhoctools.mapconfig.normalarea.details.area1.capacity     = 10
adhoctools.mapconfig.normalarea.details.area1.components   = H1-H2-H3
adhoctools.mapconfig.normalarea.details.area1.closearea    = true
adhoctools.mapconfig.normalarea.details.area1.mobilitymodel= hotspot
```

LIST 5.2 TYPICAL CONFIGURATIONS FOR A NORMAL-ACCESSIBLE AREA.

Obstacle Description File

In the aforementioned Environment Configuration File, an area can be set to a CloseArea to indicate that its boundaries will block the transmission if there is signal travelling through. In the mobility simulation, the CloseArea will cause the mobile nodes to bounce back, i.e. they can not move through the boundaries. However, the signal-blocking effect is an issue of the physical layer the network, and it is impossible to implement such an effect directly. The ns2 tool has implemented the IEEE802.11b protocol nicely, but without the knowledge of the signal-blocking obstacle in the environment. A natural solution here is that the CloseArea (Obstacle) defined in ECF can fed to ns2. A utility class SimulationUtils is designed to collect the obstacle information from the environment and output it to an Obstacle Description File (ODF). SimulationUtils is quite an important tool which does multiple jobs such as serialising the movement segments, transform the mobility modelled in this work into a ns2 compatible mobility file etc. Figure 5.10 describes this class in UML. Figure 5.11 shows an example of ODF file and its associated environment.

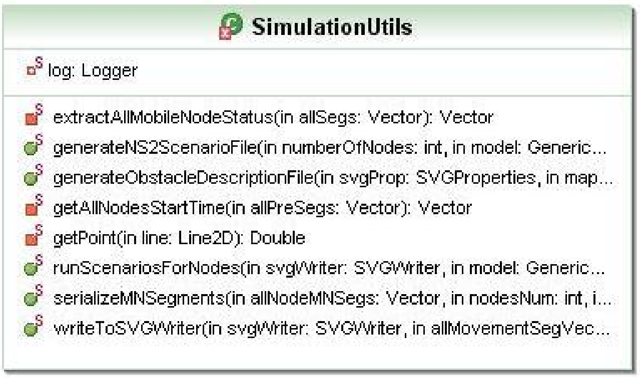


FIGURE 5.10 THE UML DIALGRAM OF THE OBJECT: SIMULATIONUTILS

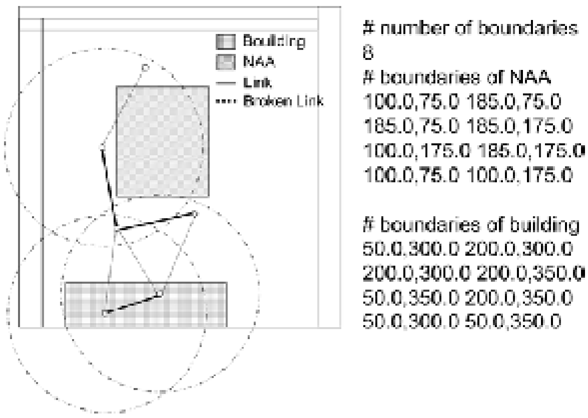


FIGURE 5.11 THE EXAMPLE OF OBSTACLE DESCRIPTION FILE (ODF) AND ITS ASSOCIATED ENVIRONMENT

The locations of both endpoints of the boundaries are recorded in ODF. So the next task is to modify the relevant ns2 source file to enable ns2 to be aware of these obstacles from ODF. Two tasks have to be done here:

- **Implementing the Obstacle C++ class (obstacle.cc) in ns2**. The boundary information comes with ODF is used to by the Obstacle class to re-construct the obstacles objects in ns2. List 5.3 shows the header file of objects.cc. The obstacle objects are initialised before at the very beginning of the simulation in ns2.

```
class Obstacle {
  public:
     Obstacle();
     void init(double x1, double y1, double x2, double y2, double x3,
double y3, double x4, double y4);
      int getObstacle(double *ax, double *ay, double *bx, double *by,
double *cx, double *cy, double *dx, double *dy);
      int Obstacle::getPoint(int i, double *ax, double *ay);
  protected:
      double x1, y1, x2, y2,x3, y3, x4, y4;
};
```

LIST 5.3 THE HEADER FILE OF THE C++ CLASS: OBJECTS

- **Modifying the physical model of ns2**. ns2 adopts the TwoRayGround propagation model which is implemented in tworayground.cc. This model is modified so that the signal strength can be effected if it finds out the signal is actually being transmitted through some boundaries whose information is stored in the obstacle objects.

5.3.4 Mobility-Concerned Simulation

Since mobility is the primary research topic, the Environment-Aware Mobility Model proposed in Chapter 4 and the mobility builder detailed in the previous sections are targeted to generate the realistic movements for the MANET research. A new simulator has not been developed as the Network Simulator 2 (ns2) which is one of the most popular network simulation tools used in the MANET research is adopted for the simulation of routing performance. Instead, a tool is developed to make the mobility information produced by this framework can be re-used in the ns2.

```
# Provide initial (X,Y, for now Z=0) co-ordinates for node_(0) and node_(1)
#
$node_(0) set X_ 5.0
$node_(0) set Y_ 2.0
$node_(0) set Z_ 0.0

$node_(1) set X_ 390.0
$node_(1) set Y_ 385.0
$node_(1) set Z_ 0.0
#
# Node_(1) starts to move towards node_(0)
#
$ns_ at 50.0 "$node_(1) setdest 25.0 20.0 15.0"
$ns_ at 10.0 "$node_(0) setdest 20.0 18.0 1.0"

# Node_(1) then starts to move away from node_(0)
$ns_ at 100.0 "$node_(1) setdest 490.0 480.0 15.0"
```

LIST 5.4 SNIPPETS OF A TYPICAL NS2 MOBILITY FILE

ns2 requires a mobility file as an input right before the simulation starts. This mobility file contains the position and movement (speed and direction) of each mobile node in the period of the simulation. List 5.4 gives some snippets from a typical mobility file. This file can be generated by a tool named ***setdest*** which comes with the ns2 packet.

In this research, the mobility information simulated can be re-used by the ns2. As mentioned before, the information of every movement epoch of any node is stored in the MNMovementSegment objects and all the movement details related to one node is available in the MovingPath object, which enables this framework to produce a ns2 compatible mobility file. The ns2 mobility file can be generated either at the end of mobility modelling or later by utilising the serialisable objects.

Therefore, the mobility modeller in this framework can be considered as a replacement tool for ***setdest*** in ns2, and it also significantly extends the capability of ***setdest*** which was of limited value and could only generate a Random-Waypoint based mobility scenario.

5.3.5 Description of Mobility Visualisation

Although there are many simulators available to help the researchers evaluate the performance of their work, most of them only provide simplistic viewers for the users to monitor or investigate the scenarios of the network and the behaviours of the mobile nodes. Those viewers are lacking in certain functions such as, colouring the nodes, visualising the transmission range, and illustrating the connectivity of the nodes, etc. All these functions are required in order to produce a better reflection on the change of the network topology of the simulated scenario, so that the researchers can have a better understanding of the results obtained from the simulation.

5.3.5.1 The Basic Animation of SVG And SVG Viewers

Scalable Vector Graphics (SVG) has been used in the mobility modeller for designing the environment, and it is also the key approach used in the mobility visualisation. With the aid of the SVG viewers which are natively supported by most of the web browsers (Microsoft Internet Explorer, Netscape Navigator, Firefox, etc), the visual presentation of the scenario can be easily rendered in real time. The build-in Zoom In, Zoom Out and Pause functions (as shown in Figure 5.12) of the SVG viewers provide even more details of the simulated scenario. With the advantages of the SVG viewers, the users are able to visually monitor the scenario of the simulation, the dynamic topology change during a certain period and even generate a snapshot of the topology at a given time.

For each simulation one SVG file is produced and it can be rendered on the SVG viewers. The entire scenario is represented in this SVG file with animation added. SVG allows both attributes and properties (e.g. colour, coordinates, etc) of an element to be animated, therefore the movement of the mobile nodes, the trace of some particular nodes, the dynamic link change and so on can be rendered on the resulting SVG file.

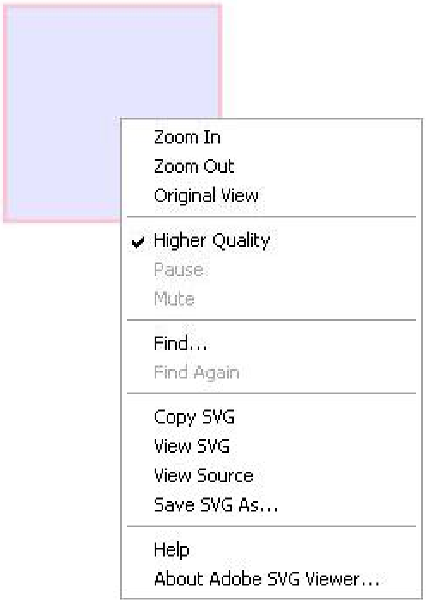


FIGURE 5.12 THE MENU OF THE SVG VIEWER SHOWS ITS FUNCTIONS INCLUDING ZOOM IN, ZOOM OUT AND PAUSE, ETC.

The element <animate> and <set> are used to render the animation. The <animate> element is used to animate a single attribute or property over time. List 5.5 shows a simple example of the usage of <animate>. The circle begins its movement at the 20th second. It moves from the location (500.0, 90.0) to (510.0, 100.0) and the movement takes 1.0 second which is defined by the attribute dur.

```
<circle id="0" cx="500.0" cy="90.0" r="4.0" fill="blue" stroke="purple">
   <animate attributeName="cx" attributeType="XML" begin="20.0"
dur="1.0" fill="freeze" to="510.0" from="500.0" />
   <animate attributeName="cy" attributeType="XML" begin="20.0"
dur="1.0" fill="freeze" to="100.0" from="90.0" />
</circle>
```

LIST 5.5 EXAMPLE CODES SHOW A SIMPLE USAGE OF TAG <ANIMATE> OF SVG

The <set> element provides a simple way of setting the value of an attribute for a specified duration. List 5.6 shows a simple example of the usage of <set>. The line starts at (500.0, 90.0) and ends at (520.0, 105.0) will be invisible for 2 seconds from the 30th second after the SVG is rendered. At the 32nd second, it becomes visible again.

```
<line id="00to10" x1="500.0" y1="90.0" x2="520.0" y2="105.0">
   <set attributeName="visibility" attributeType="XML" begin="30.0" dur="2.0" fill="freeze" to="hidden" />
   <set attributeName="visibility" attributeType="XML" begin="32.0" dur="2.0" fill="freeze" to="visible" />
</line>
```

LIST 5.6 EXAMPLE CODES SHOWS A SIMPLE USAGE OF <SET> IN SVG

5.3.5.2 Visualisation of The Simulated Scenario

The non-environment elements, such as the mobile nodes, the link between two neighbour nodes and the antenna range can also be represented with the basic shapes defined in SVG.

Usually the mobile node is presented as a tiny circle, the antenna range is indicated by a larger circle with its radius equal to the actual transmission range, and a line connects the neighbours nodes is used to indicate a link. All these elements can be identified by a unique identifier (namely, the value of the attribute *id*) and visually differentiated by assigning different values to their attributes. With this design and the animation support of SVG, it is possible to provide functionalities such as colouring the nodes, setting the antenna transmission range, showing/hiding the node at run time. For example, a circle centred by a node can be moving together with the node to indicate the change of the antenna coverage; the colour of the nodes is changed if they are located inside the circle to indicate that they become the neighbour nodes with one hop connection.

A configuration file, Output Configuration File (OCF) shown in Figure 5.2 can be used to customise the output SVG file. This file consists of two section: the global parameters used by the output SVG file, including the width, the height, the bordercolor etc, and the setting for the presentation of various mobile nodes, such as: the node colour, the antenna colour, the node visibility etc.

An example of this configuration file is shown in List 5.7. The lines 2-7 are the setting for the SVG layout and the rest of lines define the setting for the mobile nodes. Note that the 'svg layout properties' section and the 'default node properties' sub-section are mandatory in this file because the former will be written into the root element of a SVG file and the latter will be used as the default setting for the presentation of all the mobile nodes.

In Chapter 4, node heterogeneity is introduced; therefore the nodes should be able to be given different settings in order to differentiate each other on the SVG. This can be done in this configuration file. The Lines 20 to 26 show the setting particularly for the presentation of bus nodes. According this configuration, the bus nodes will be represented in a blue colour and its antenna range (the circle around it) is set to 150 meters, and the rest of nodes are in black, their antennas will not be shown but the nodes will drop an orange ‘footprint’ for tracking.

```
1    # svg layout properties
2    adhoctools.svgconfig.layout.width          =25cm
3    adhoctools.svgconfig.layout.height         =20cm
4    adhoctools.svgconfig.layout.viewBoxX       =1000
5    adhoctools.svgconfig.layout.viewBoxY       =1000
6    adhoctools.svgconfig.layout.grid           =visible
7    adhoctools.svgconfig.layout.bordercolor    =black
8    #
9    # the default node properties
10   #
11   adhoctools.svgconfig.default.antenna.visibility   = hidden
12   adhoctools.svgconfig.default.antenna.rxrange  = 100
13   adhoctools.svgconfig.default.antenna.color = grey
14   adhoctools.svgconfig.default.node.visibility  = visible
15   adhoctools.svgconfig.default.node.color       = black
16   adhoctools.svgconfig.default.node.pathcolor   = orange
17   #
18   # bus node properties
19   #
20   adhoctools.svgconfig.node.busnode.color       = blue
21   adhoctools.svgconfig.node.busnode.fillColor      = blue
22   adhoctools.svgconfig.node.busnode.visibility     = visible
23   adhoctools.svgconfig.node.busnode.antenna.visibility = hidden
24   adhoctools.svgconfig.node.busnode.antenna.color      = grey
25   adhoctools.svgconfig.node.busnode.antenna.rxrange = 150
26   adhoctools.svgconfig.node.busnode.pathcolor      = default
```

LIST 5.7 EXAMPLE OF OUTPUT CONFIGURATION FILE (OCF)

The main settings for the mobile nodes are detailed in Table 5.1

TABLE 5.1 THE DESCRIPTION OF THE MAIN SETTINGS FOR THE MOBILE NODES IN THE FILE SVGCONFIGURATION.PROPERTIES

Setting	Description	Value
node.color	The colour of the border of the tiny circle used to present the node in the SVG file	Any colour supported by SVG, such as blue, red etc, the default value is **black**
node.fillColor	The colour of the filling of the tiny circle used to present the node in the SVG file	Any colour supported by SVG, such as blue, red etc, the default value is **black**
node.visibility	the nodes will (not) be represented in the SVG file	**visible** or **hidden**
antenna.visibility	the antenna of the node will (not) be presented in the SVG file	**visible** or **hidden**
antenna.rxrange	The communication range of the antenna	The default value is set to **100 in meters**
antenna.color	The colour of the antenna in the SVG file	Any colour supported by SVG, such as blue, red etc, the default value is **black**
node.pathcolor	The colour of the path the nodes travel along during the simulation	Any colour supported by SVG, such as blue, red etc, the default value is **black**

5.3.5.3 Snapshots of Network Topology

Sometimes the network performance looks fine in general but it also turns out that in some situation the performance significantly dropped. Without the visual knowledge of the network topology at some particular time, it is very hard to find the solution to improve the protocol. In the framework, a handy function has been developed to generate a snapshot of the network topology in the SVG format. By deserialising the .ser files mentioned in an early section, a SVG file can be produced presenting the topology of the network at a given simulation time, along with the links between neighbour nodes. Figure 5.13 gives an example snapshot of the topology of a simple mobile ad hoc network. The grey line connecting two nodes indicates that these two nodes are within communication range of the antenna.

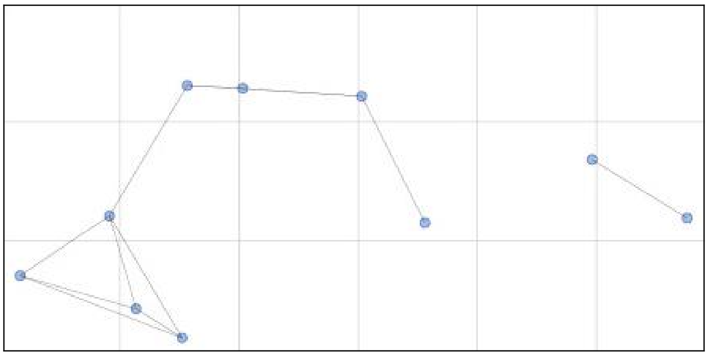


FIGURE 5.13 THE SNAPSHOT OF THE NETWORK TOPOLOGY AT 60TH SECOND

5.3.5.4 The Dynamic Topology Change

Instead of being interested with the topology at the particular time, the user may want to check out the topology change during a particular period when they found a significant fluctuation in the network performance. Instead of producing a static SVG file, an animation file can be generated to reflect the dynamic topology change by specifying the interested period, i.e. the start time and stop time of the period.

Figure 5.14 demonstrates the dynamic topology change from the 10th seconds until 100th seconds. The snapshots were taken at 10th, 15th, 50th and 100th second. With this powerful feature, not only the movements of the nodes, but the link changes can be explicitly monitored.

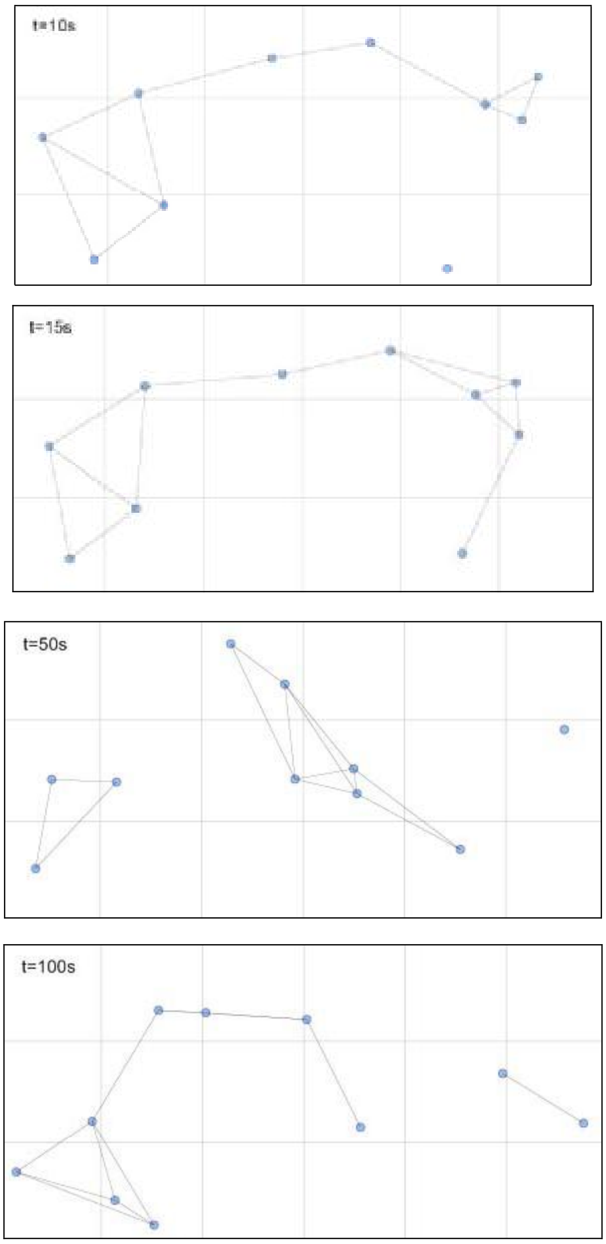


FIGURE 5.14 THE DEMONSTRATION OF THE DYNAMIC TOPOLOGY CHANGE FROM 10TH SECOND TO 100TH SECOND

5.3.5.5 Visualisation of The ns2 Scenario File

The mobility scenario file used by ns2 has been introduced in section 5.3.4. ns2 lacks the function of visualising scenarios nicely, it is necessary to build a tool to enable ns2 output to be visualised. Furthermore, a SVG file can be rendered in a browser with the scripting language (i.e. Javascript) embedded. This provides additional interactivity so that users can manipulate the SVG to get more information. As a part of this framework, a web-based tool called ns2svg Mobility Visualiser has been developed. Figure 5.15 shows the interface when the Visualiser is running. The location of each mobile node can be recorded and updated on the browser on the left-side of the interface instantly. The rectangle area on the right-hand side is the demonstration of the network topology simulated by ns2. In this case, the simulation area is 300x600m and 50 mobile nodes were simulated. By clicking the node, a circle appears to illustrate the antenna transmission range of this node, and all the nodes located in this range are considered as its neighbour nodes which are given a different colour. The colour of the nodes can also be updated automatically when the nodes move in or out of the transmission range of the nodes nearby.

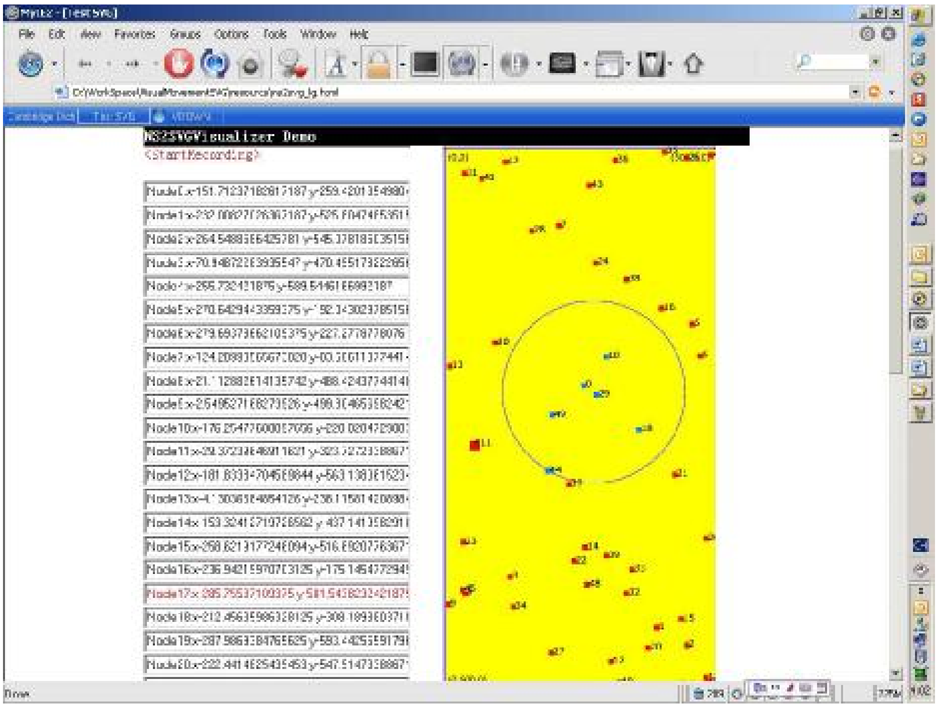


FIGURE 5.15 THE SCREENSHOT OF NS2SVG MOBILITY VISUALISER CAPTURED DURING ITS RUNTIME

5.3.6 Description of Performance Evaluation Tools

Several performance evaluation tools have also been developed in this framework to measure both connectivity-related metrics and routing-related metrics in the mobility-concerned environment.

5.3.6.1 Connectivity-related Metrics

As mentioned before, the movements of all the mobile nodes during the simulation are recorded into serialised movement segments and physically stored in files on the operation system. One usage of these files is to generate the connectivity-related metrics to help to better measure the topology change of the networks during the simulation time. The Connectivity-related metrics can be easily computed from the topology graph of the network [70]. The snapshots of the network topology are taken at a regular time interval, t_s. Note that the value of t_s depends on the level of the mobility of the mobile nodes. In order to achieve higher accuracy for a fast changing topology, the snapshot interval should set to a very small value, e.g. $t_s \le 1s$. The metrics are measured repeatedly during a starting time t_{start} to a stop time t_{stop} which normally are the starting and finishing time of the simulation. In order to calculate a metric at a specific time point (t_n), the position of all the nodes at t_n must be obtained and the topology graph should be created. With the availability of MovingPath objects, the location of each node in the network at t_n can be easily retrieved.

When the locations of all the nodes are obtained, the next step is to create the topology graph. Considering a mobile ad hoc network with N nodes, G_{t_n} is used to denote the graph created at time t_n, the edge for any two nodes $j,k \in N, j \ne k$ can be calculated as follows:

$$e_{j,k} = \begin{cases} 1 \text{ if } D_{j,k}^{t_n} \le r \\ 0 \text{ otherwise} \end{cases} \tag{5.1}$$

Where $D_{j,k}^{t_n}$ is the distance between the nodes j and k at time t_n. The graph G_{t_n} and its associated adjacency matrix M_{t_n} are the essential data used for the measurement of the connectivity-related metrics. From the adjacency matrix M_{t_n} the number of partitions in the entire mobile ad hoc network is computed by performing the Depth-First Search

(DFS) algorithm [82]. The search algorithm returns a set of groups, $\Gamma = \{\gamma_0, \gamma_1, ... \gamma_n\}$ each γ_n represents a partition which contains a percentage of the nodes in the network.

The following metrics can be calculated:

Number of Partitions ($\overline{\boldsymbol{P}}$) – It is the number of partitions returned by the DFS algorithm, $\boldsymbol{P} = |\Gamma|$. The larger the value of P is, the more fragmented the mobile ad hoc network is. If $\boldsymbol{P} = \mathbf{1}$, it means the network is fully connected.

Largest Partition ($\overline{\boldsymbol{LP}}$) – Going through the group γ_n of the set Γ, the one with the largest number of members can be easily found,

$$L = \operatorname{argmax}_{\gamma \in \Gamma} |\gamma| \tag{5.2}$$

$$\overline{\boldsymbol{LP}} = |L| \tag{5.3}$$

Where L is the largest partition in Γ, and $\boldsymbol{LP}$ is the size of L, i.e. the number of members in this partition. The larger the $\boldsymbol{LP}$ is, the more mobile nodes are able to communicate with other nodes in this network. The ideal value of $\boldsymbol{LP}$ should be equal to the total number of nodes in the network, i.e. $\boldsymbol{LP} = N$.

Normalised Unreachable Pairs ($\overline{\boldsymbol{NU}}$) – If there is no path between two nodes, this pair of nodes will be considered as unreachable nodes [83]. From the adjacency matrix M_{t_n}, the *distance matrix DM* can be created by computing the shortest path from one node *i* to all the other nodes *j* in the network. So the shortest path $DM_{ij}, i \neq j$ connects the node *i* and *j* is defined as the path with the smaller number of hops between both nodes. If $DM_{ij} = 0, i \neq j$, it means the node *j* is not reachable from node *i*, and a counter *c* is incremented by one, then we have:

$$c = c + 1 \text{ if } DM_{i,j} = 0, i \neq j$$

The total number of pairs of the network is given by $c_{total} = N(N-1)$ and the normalised number of unreachable node pairs now can be calculated by:

$$\boldsymbol{NU} = \frac{c}{c_{total}} \tag{5.4}$$

The higher the value of this metric is, the lower the connectivity of the network is.

5.3.6.2 Routing-related Metrics

ns2 is a powerful tool, but unfortunately it does not provide any tools for analysing the simulation results. It simply simulates a network, and provides a so-called trace file of all the events that occurred during the simulation. The framework provides a set of tools written in ***awk*** [84] scripts which can be used to compute three key routing-related metrics including the delivery rate, the end- to-end delay of the data packets and the routing overhead. In the routing process the timely delivery of the packets is crucial. Delays caused by some routing mechanism such as the route discoveries, traffic collision etc affect the performance of the network services at higher layers. Because of the limited bandwidth of wireless network, the network overhead (the control packets required to be transmitted for some routing routines such as routing table maintenance) have to be kept as low as possible.

Delivery Rate (*DR*), concerns the efficient delivery of all the transmitted data packets from the source nodes to the destination. This metric is calculated as the ratio of the number of successfully received data packets over the number of actually transmitted data packets. *DR* is:

$$DR = \frac{P_{received}}{P_{transmitted}} \tag{5.5}$$

where $P_{received}$ are all the packets in the ns2 trace file with the event-flag equal to r and $P_{transmitted}$ is the total number of the transmitted packets in the trace file, with the event-flag equal to s. This metric can be calculated either on a per node basis and then summed up or as the overall number of packets exchanged between the nodes in the network. The possible values of the delivery rate range between 0 and 1. Higher values on the delivery rate indicate a better functioning network.

End-to-End Delay (*EED*), concerns the timely delivery of the packets. Normally when the data packet is transmitted, a timestamp is stored in the header of the packet. Once this packet is successfully received by the destination, the *EED* can be calculated by

$$EED \quad \frac{\sum_{1}^{N_{received}} t^{p}}{N_{received}} \tag{5.6}$$

Where $t^p \quad t^p_{received} - t^p_{transmitted}$ is the transmission delay of packet $p, N_{received}$ is the total number of packets received. The delay t^p is the sum of a number of delays, such as the ***queueing delays*** caused by the collisions or route discovery by the intermediate nodes and ***transmission delay*** which is the time taken for the transmission from one node to the next. Usually high node density networks will cause higher end-to-end delay of a packet than low node density ones.

Routing Overhead (*RO*) also called Network Throughput is calculated as the total number of control packets sent during the simulation by the routing protocols. If the number of control packets sent by the node *n* is P_n, then the total control packets sent during the simulation by all the nodes can be obtained by

$$RO = \sum_1^N P_n \tag{5.7}$$

where *N* is the number of nodes in the network.

In Chapter 6 when the simulation results are analysed, the discussion of these three routing-related metrics will be detailed in different simulated networks.

5.4 CONCLUSIONS

The Environment-Aware Mobility (EAM) model introduced in Chapter 4 need be implemented for simulation and evaluation together with network protocols, therefore a set of tools are required in the framework. These tools are detailed in this chapter. A new mobility modeller for mobile ad hoc networks is included in this framework. This modeller can be used for modelling the conventional mobility models, but more importantly, it can also model the environment where the networks are deployed by introducing the technology of SVG to represent the environment objects discussed in Chapter 4. By taking the advantage of animation feature of SVG, a tool for visualizing the mobility of mobile nodes and the changing of the network topology is also developed in this framework. The mobility information generated by the framework can be fed to the ns2 simulator for network simulation. A set of evaluation tools was also developed for the measurement of both connectivity-related metrics and routing-related metrics. The framework is designed with the concern of scalability. Other researcher can take the advantage of the structure of the this framework, i.e. the generic mobility model, environment design and configuration, measurement tools and so on for the research of their mobility models for particular environments. The technology of Serialisation is implemented into this framework. The mobility information of each mobile node be serialised into files which can deserialised later for other purposes. For instance, the emulator which will be introduced in Chapter 7 is using the resulting files of serialisation for the knowledge of mobility of mobile nodes.

The simulation and evaluation results are presented in Chapter 6.

Chapter 6: SIMULATION RESULTS AND PERFORMANCE ANALYSIS

6.1 INTRODUCTION

Four parts of this research have been addressed, the self-positioning and location-label based routing protocol proposed in Chapter 3, the Environment-Aware Mobility model along with two sub-models (Route model and Hotspot model) and the special IVC systems (RoadLamp-aided IVC system and Bus-aided IVC system) introduced in Chapter 4 and a set of tools included in the framework for the mobility concerned simulation was described in Chapter 5. The aim of this chapter is to present the simulation results and evaluate the performance of the entire research works. Since the four parts of this research focus on different issues of mobile ad hoc networks, different methodologies are used for the performance evaluation of each part. Network Simulator 2 (ns2) is heavily used in this research for the simulation of routing protocols. Default parameters for the ad hoc networks defined in ns2 are used and the important ones are listed in Table 6.1. Note that the general impact of the mobility of mobile nodes and the environment on the network performance are the key issues this thesis focus on, and also to simplify the research, the influence caused by some other issues such as types of traffic, types of applications etc was not included in this thesis.

TABLE 6.1 IMPORTANT DEFAULT SETTINGS FOR AD HOC NETWORKS IN NS2

Parameters	Value
MAC Protocol	IEEE 802.11b
Data rate for MAC	2Mbps
RTS/CTS	On
Preemble	Sending rate: 1Mbps; Length: 128bits
Channel	Noise free channel

In the following sections, the methodologies and the results from the evaluation are given.

6.2 GPS-FREE SELF-POSITIONING ALGORITHM AND LOCATION-LABEL BASED ROUTING (LLBR)

Network Simulator 2 (ns2) is a discrete event simulator targeted at networking research. NS2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (with CMU Monarch extension [96]) networks. It was used to simulate the Mobile Node Positioning Algorithm and the LLBR protocol.

The behaviour of the Centre Node and the positioning procedure running in other nodes is illustrated by Figure 6.1 and Figure 6.2. When the centre node is chosen, it starts to generate the Reference Coordinate System (RCS), calculates the offset & rotation angle for the conversion of the coordinates and carries out the Y-flip if necessary.

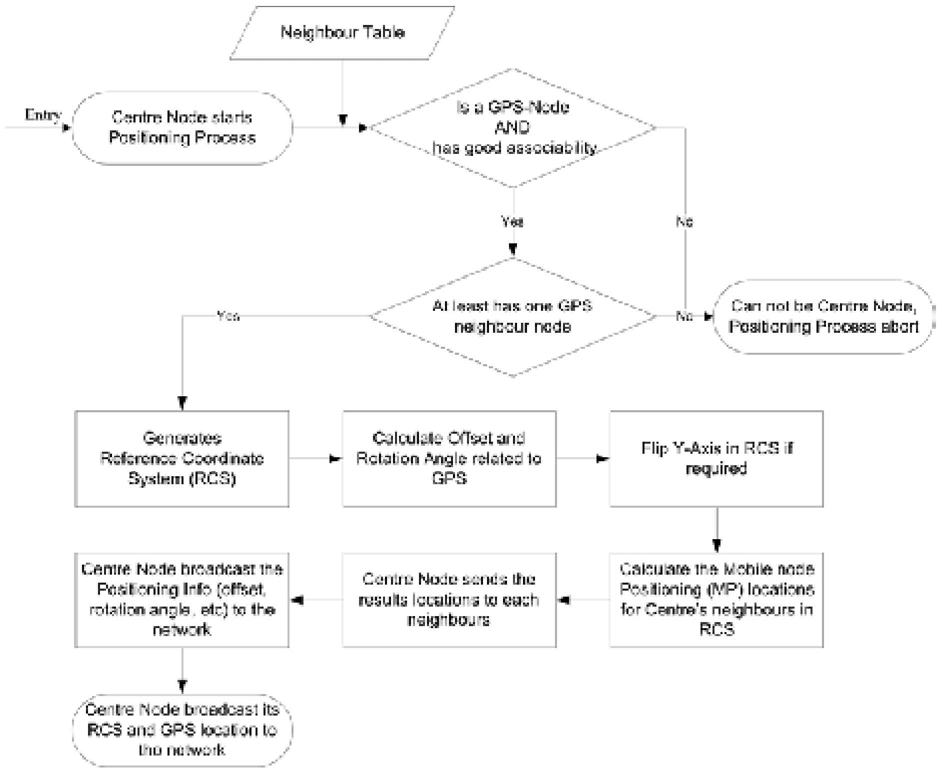


FIGURE 6.1 ILLUSTRATION OF THE POSITIONING PROCEDURES FOR THE CENTRE NODE

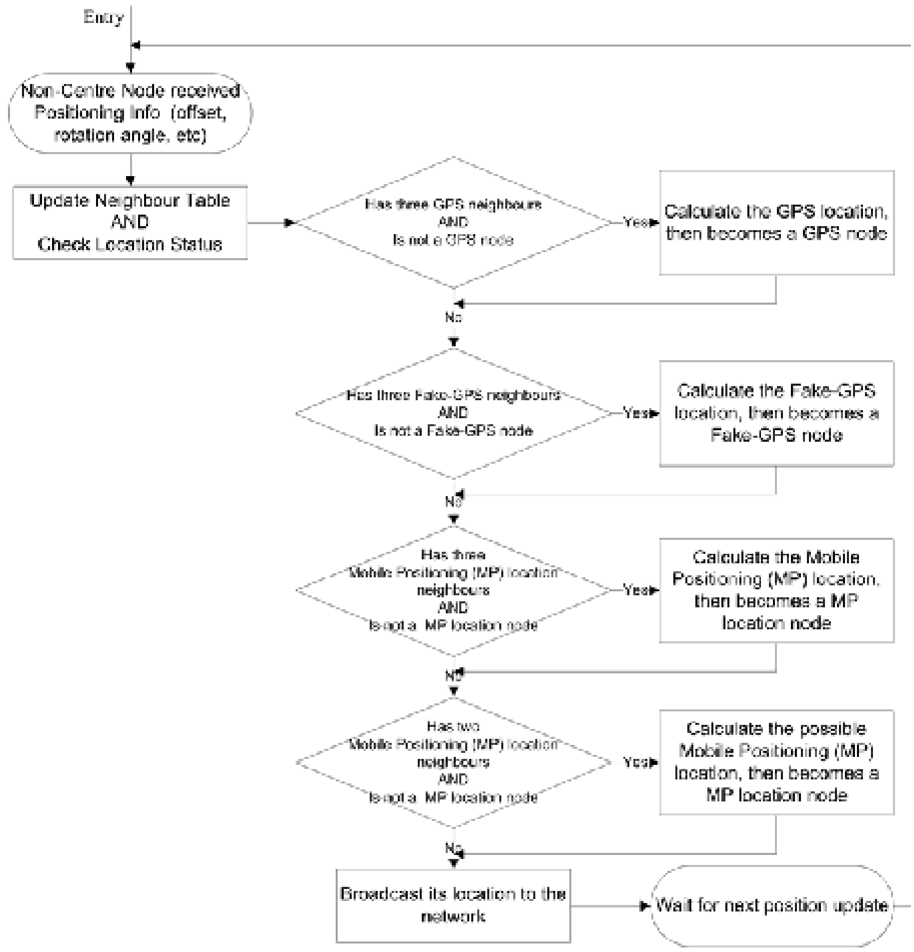


FIGURE 6.2 ILLUSTRATION OF THE POSITIONING PROCEDURES FOR THE NON-CENTRE NODES

Since the locations of centre' neighbours in Mobile node Positioning (MP) Coordinate System are all calculated by the centre, the centre needs to inform each neighbour after the calculation is finished. After that, all the positioning related information is broadcasted to the network with the Positioning Packet. Every Mobile Node (MN) checks its location status, i.e. finds out if it has MP location or Fake-GPS location or not. According to status, MN can decide which procedure must be taken. Considering the fact that the MP Coordinate System or Fake-GPS coordinates system could be stale due to the mobility of MN, the positioning must be triggered every so often. The centre ID is and an update-sequence number are included in the Positioning Packet. The MN needs to compare the incoming update-sequence number with its locally stored one and only participate in the next round of positioning if the incoming number is larger. If the selection of the centre is taken into account, more fields are required to be inserted into the Positioning Packet as discussed in Chapter 3. Figure 6.3 illustrates the procedures when the node is notified from the Positioning Packet received there is new round of positioning is required. The location of either the MP location or Fake-GPS location is broadcasted by the MNs when they receive the positioning information and done the calculation.

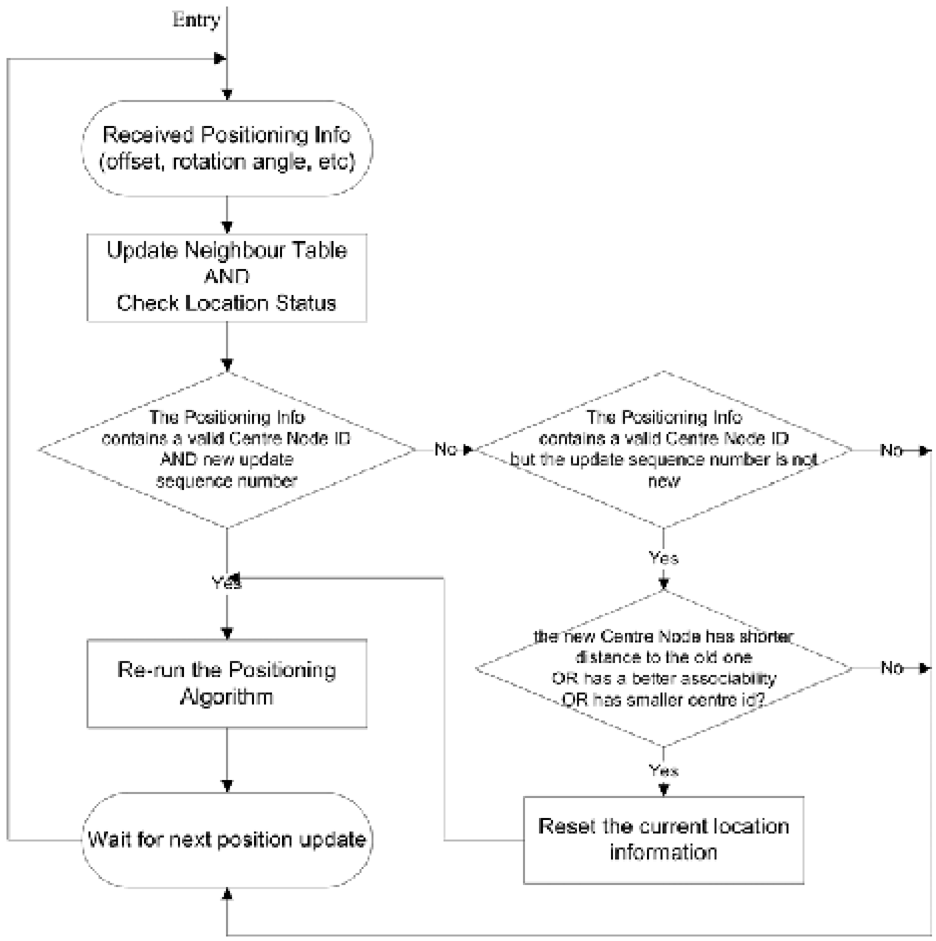


FIGURE 6.3 ILLUSTRATION OF THE PROCEDURES WHEN THE MOBILE NODE RECEIVES A POSITIONING PACKET WITH NEW ROUND OF POSITIONING REQUIRED

Figure 6.4 and Figure 6.5 illustrates the main procedures that occur in Routing Stage of LLBR. There are five types of packets which could be received by the mobile nodes when

LLBR is operating, Hello Packets, Positioning Packet, Data Packet, Location Packets and Reply Packet. Figure 6.4 details how the mobile node responds when it receives a packet, and Figure 6.5 gives the details when the mobile node sends a Data Packet.

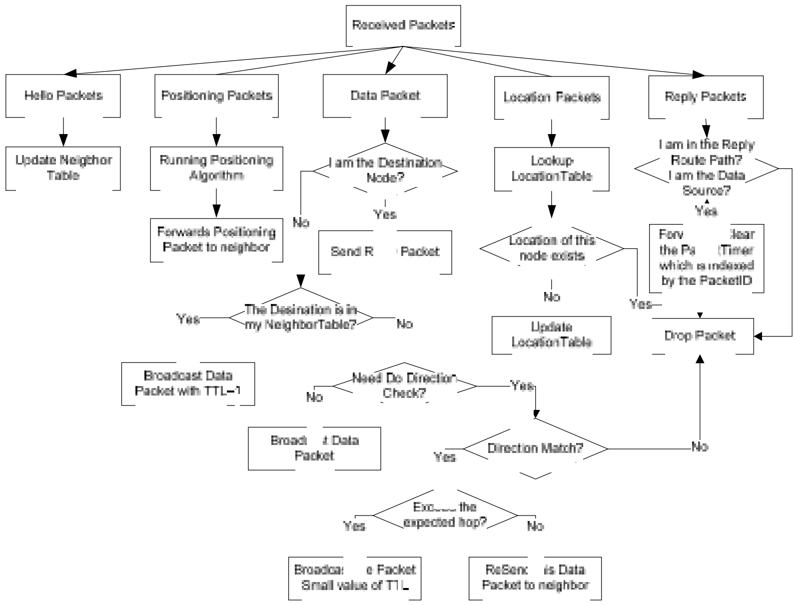


FIGURE 6.4 ILLUSTRATION OF THE PROCEDURES WHEN A PACKET IS RECEIVED BY A MOBILE NODE

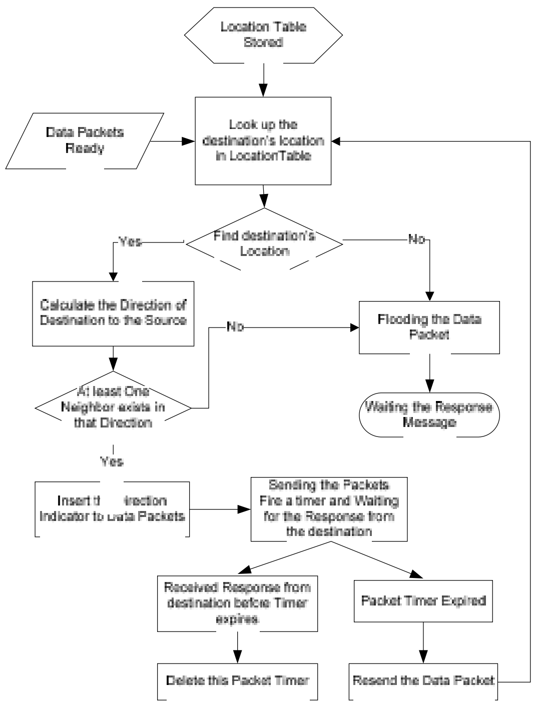


FIGURE 6.5 ILLUSTRATION OF THE PROCEDURES WHEN MOBILE NODE NEED SEND A DATA PACKET

When the Data Packet is ready for transmission, the source node searches the neighbour table and the location table. If the destination is the neighbour of current source node, the data are broadcasted with TTL set to 1 in order to reduce unnecessary DI check in the receivers. If the destination's location is known by the source, DI is calculated and inserted into the head of data. Currently, a flooding method is implemented when the destination's location is unknown or no neighbour with the same direction of destination can be found. Once the data packet is sent out, a timer indexed by the packet ID is triggered and the source node waits for the Reply Packet from the destination to confirm reception. If no Reply Packet is received before the timer expires, the same copy of the original data is retransmitted. When the nodes get the data packet, the procedure is quite straightforward, i.e. send Reply Packet to source node if it is the destination. If it is not the destination, the first thing to do is to check the neighbour table and make sure the destination is recorded. The data will be broadcasted again with TTL set to 1, and if not, this intermediate node is going to check the Direction Indicator Byte (DIB). As described before, only DIB matched nodes can be routing nodes and re-send the data, otherwise the packet will be ignored. In order to overcome the drawback of the LLBR that it does not consider the movement of the destination, a MAX-Hops is counted by Distance_to_Destination/Average_Hop before the data is sent by the source. When the routing node finds that the hops at the time the packet is received has exceeded the MAX-Hops, it assumes that the destination had moved away and can not be reached by DI check later on. In this case, the data is broadcasted with limited TTL. Using these ideas, the data is relayed to the destination and the resulting overhead result from routing is reduced. Figure 3.14 illustrates the routing path. On the other hands, the Reply Packet can be forwarded by either INVERT_ROUTE or FLOODING. The former method is more efficient when the mobility of the nodes is low because the invert-route is still available, and flooding is the choice in a high mobility network. By INVERT_ROUTE, only the routing node of that data packet can be allowed to forward the Reply Packet towards the source node. When the reply gets to the source, the specific timer is cancelled because the transmission has been successfully confirmed.

6.2.1 Mobile Node Positioning Simulation Result

In this section, the simulation results are presented to show the performance of the positioning algorithm. Four examples for the node connectivity will be given in the first section. In the second section, the MP Coordinate, Fake-GPS Coordinate and GPS Coordinate give the visual demonstration of the result and illustrate the difference among them. The accuracy of the position is the key factor in the performance evaluation. The accuracy is tested under the condition with different level of the node mobility, the connectivity and GPS rate, etc.

Several scenario files were created for each situation by using ns2. In each scenario file the destinations of movement for each node, average speed of nodes, pause time, simulation area, simulation time, etc are defined.

6.2.1.1 Node Connectivity in MANET

The connectivity is one of the key factors influencing the performance of the position algorithm. With the different power ranges of the antenna, the connectivity of the target MANET can change dramatically. Figure 6.6 illustrates the change in connectivity. The performance of the connectivity will be discussed later this chapter. In this research, the antenna power range is set to 250m which is the default configuration in ns2.

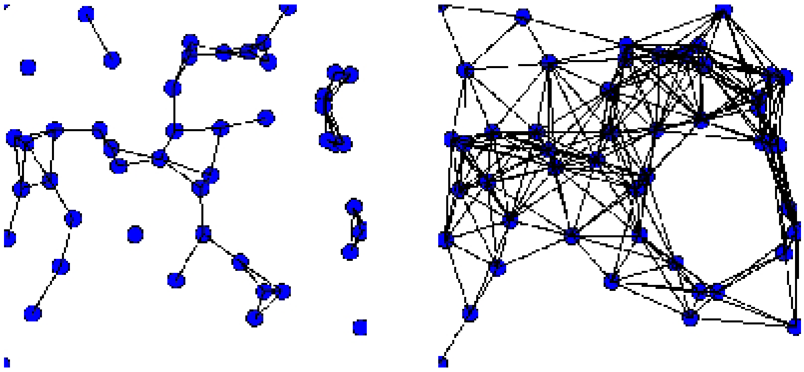
6.2.1.2 Comparison on Three Coordinate Systems in MANET

6.2.1.2.1 MP Coordinate & Fake-GPS Coordinate

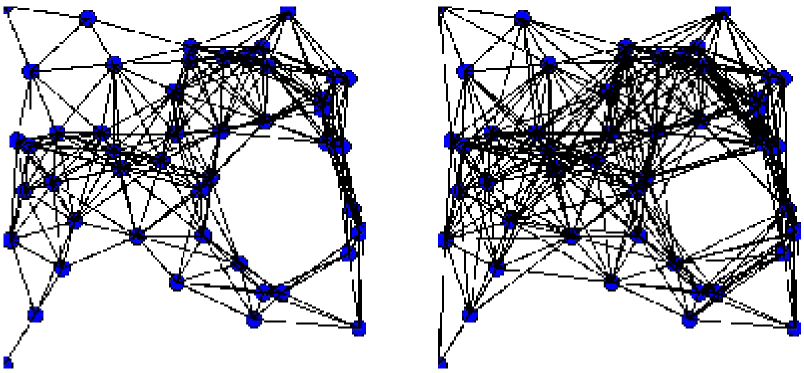
As shown in Figure 6.7(a), 50 nodes are simulated to generate its GPS-free MP position. The node in (0, 0) is the centre node selected to begin the positioning. It must be a GPS node and have a GPS neighbour. The GPS location is the offset which is broadcasted in the MANET and the rotation angle is counted according to the GPS location and MP location of the GPS neighbour.

Based on the algorithm, the Fake-GPS Coordinate is a conversion coordinates by offsetting and rotating the MP Coordinate. The final Fake-GPS Coordinate is showed in Figure 6.7(b). If the Figure 6.7(a) is rotated and offset, it can found out that the nodes printed on it are overlapped on the nodes on Figure 6.7(b). For example, node A on

Figure 6.7(a) overlaps on node A' of Figure 6.7(b); the location of node B on Figure 6.7(a) matches node B' of Figure 6.7(b).



(a) Antenna Receive Range = 100m (b) Antenna Receive Range = 150m

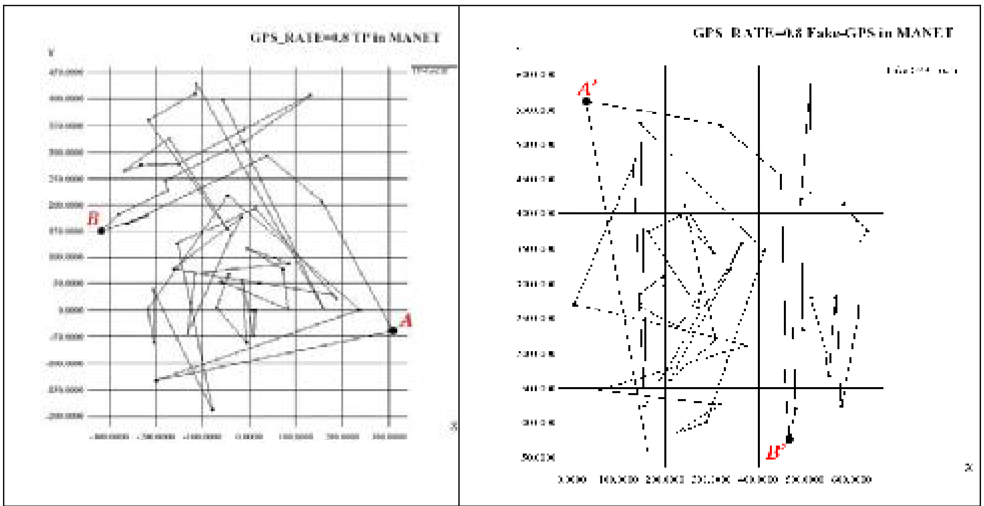


(c) Antenna Receive Range = 200m (d) Antenna Receive Range = 250m

FIGURE 6.6 ILLUSTRATION OF NODE CONNECTIVITY WITH DIFFERENT POWER RANGE [NUMBER OF MOBILE DODE = 50, AREA 670X670(M^2)]

6.2.1.2.2 GPS Coordinate & Fake-GPS Coordinate

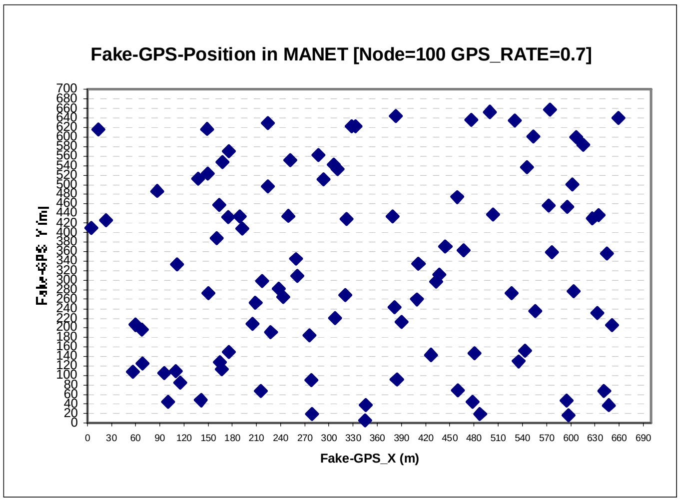
Fake-GPS is the Coordinate we wish to get in this project to replace the GPS Coordinate wherever the MANET locates. The best result is that the node position in Fake-GPS Coordinate can completely match the position in GPS Coordinate.



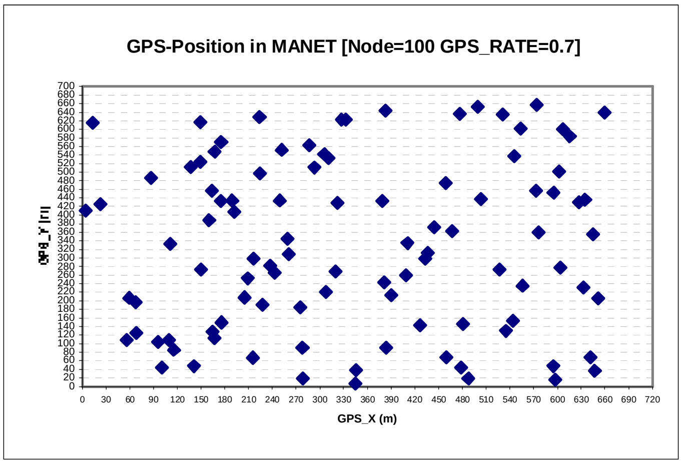
(a) Position in GPS-free MP Coordinate System	(b) Fake-GPS Coordinate System after offsetting and rotating MP Coordinate System

FIGURE 6.7 THE COMPARISON ON THE MP POSITION AND FAKE-GPS POSITION

Figure 6.8 shows a best result sample when simulate 100 nodes and the GPS rate is 0.7 in 670x670m^2 area.



(a) The locations of mobile nodes in the Fake-GPS Coordinate System



(b) The locations of mobile nodes Position in the GPS Coordinate System (completely matches Fake-GPS position)

FIGURE 6.8 THE COMPARISON OF THE FAKE-GPS POSITION AND GPS POSITION

6.2.1.3 Accuracy Test

There are many factors that could influence the performance of the positioning algorithm, such as the node speed, the network topology, the positioning update interval, the connectivity, etc. The accuracy is tested against the GPS_Rate, i.e. the percentage of GPS-nodes in the network), Number of Nodes, Average Speed of Nodes, Update Interval and the Connectivity. The Accuracy is defined as the following:

$$Accuracy = \frac{\sqrt{(Fake\_GPS\_X - GPS\_X)^2 + (Fake\_GPS\_Y - GPS\_Y)^2}}{\sqrt{(MAX\_X - MIN\_X)^2 + (MAX\_Y - MIN\_Y)^2}} * \frac{1}{N_{node}} \quad (6.1)$$

where:

MAX_X = maximum X position in simulation area
MIN_X = minimum X position in simulation area
MAX_Y = minimum Y position in simulation area
MIN_Y = minimum Y position in simulation area
N_{node} = Amount of Nodes in simulation

In all the tests, we define:

MAX_X = *MAX_Y* = 670m

*MIN*_X = *MIN*_Y = 0m

6.2.1.3.1 GPS_RATE vs. Accuracy

In this test, the GPS_RATE is changed from 0.2 to 1.0. A GPS_RATE of less than 0.2 was not used as no centre node can be found in MANET when there are 50 nodes in simulation (low connectivity). At this stage, the node speed is not taken into account, which means the position was obtained right after the node executed the position algorithm. Further tests showed that the performance also depends on the update interval and the mobility.

As shown in Figure 6.9, when the GPS_RATE reaches 0.35~0.4, the accuracy is almost 1.00 which is a very good performance. Even in scenario3, the worst accuracy is obtained when GPS_RATE=0.2, and the position error is about 110m as computed with Equation 6.1 and the result can still be viewed as acceptable if it is considered that the real GPS precision is normally about 100m.

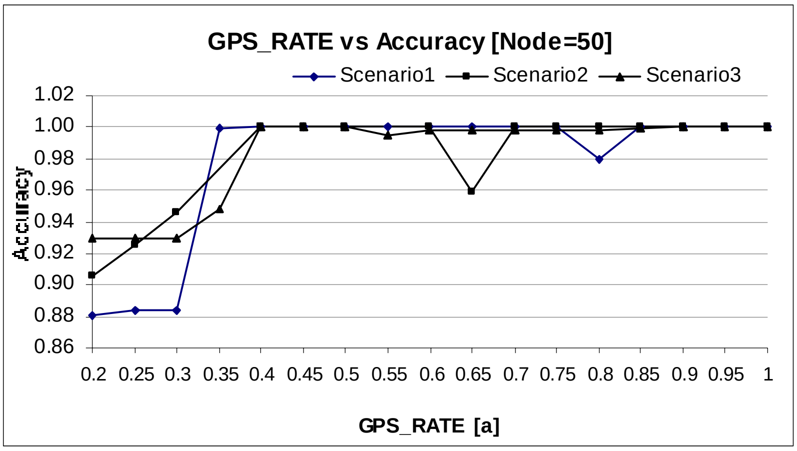


FIGURE 6.9 SELF-POSITIONING SIMULATION RESULTS - THE GPS_RATE VS. ACCURACY [ANTENNA POWER RANGE = 250M]

6.2.1.3.2 Number of Nodes vs. Accuracy

The number of the nodes in MANET is plotted against different GPS_RATE. Figure 6.10 shows the result. The higher the GPS_RATE and the more nodes, the higher the accuracy can be achieved. When the nodes are reduced to 20 and GPS_RATE = 0.3, the results are not valid. The reason is that the resulting connectivity could be too low when the amount of nodes are changed but the simulations are still run in the same simulation area,.

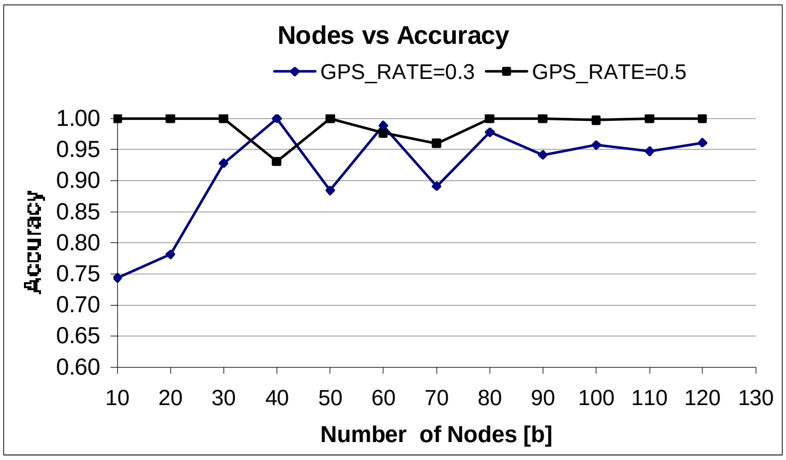


FIGURE 6.10 SELF-POSITIONING SIMULATION RESULTS – NUMBER OF MOBILE NODES VS. ACCURACY, SIMULATED WITHIN THE SAME SIMULATION AREA

6.2.1.3.3 Average Speed vs. Accuracy

During the interval between two positioning times, the MNs may move to another locations. If the routing algorithm uses the location information, packets may be lost. This test is implemented at the beginning of each positioning time (just before the update procedure). Figure 6.11 shows that radio traveling at high speed will corrupt the algorithm.

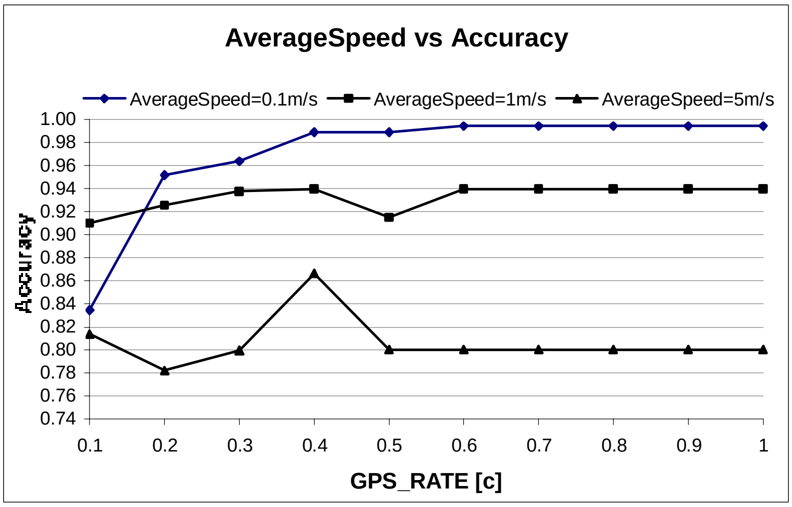


FIGURE 6.11 SELF-POSITIONING SIMULATION RESULTS - THE AVERAGE SPEED VS. ACCURACY [POSITION INTERVAL = 60S]

6.2.1.3.4 Update Interval vs. Accuracy

The performance tested in Figure 6.11 can be improved by reducing the position update interval. As shown in Figure 6.12, when the position update interval is reduced to 5 simulation seconds, a perfect performance can be achieved. The problem is that there will be a trade-off between the update interval and the network traffic. Shorter intervals can cause higher traffic in the MANET because more HELLO messages are required to be broadcasted. In future research, these two factors must be considered and adjusted carefully.

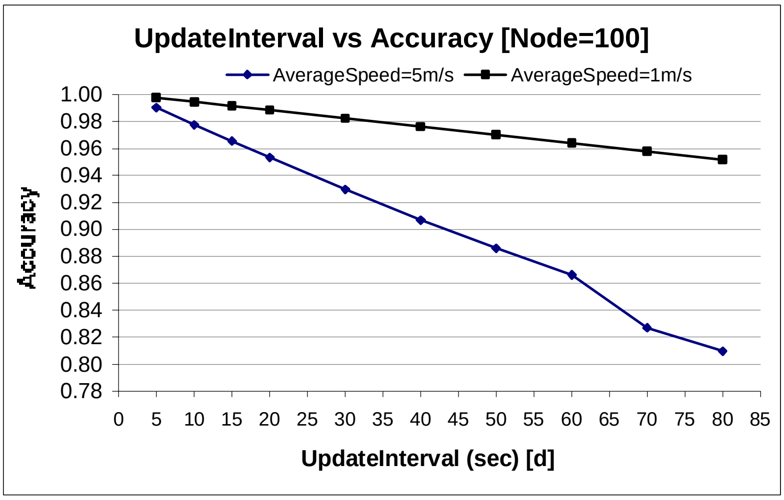


FIGURE 6.12 SELF-POSITIONING SIMULATION RESULTS - UPDATE INTERVAL VS. ACCURACY [NUMBER OF MOBILE NODE=100]

6.2.1.3.5 Connectivity vs. Accuracy

Analysing the worst results obtained from each test, connectivity turns out to be an essential factor influencing the performance. By tuning the power range of the antennas of mobile nodes, the positioning algorithm is simulated in difference connectivity. The results are illustrated in Figure 6.13.

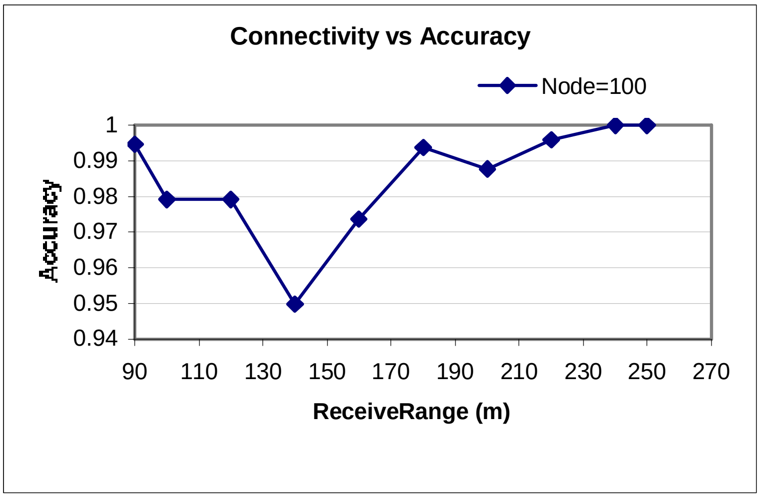


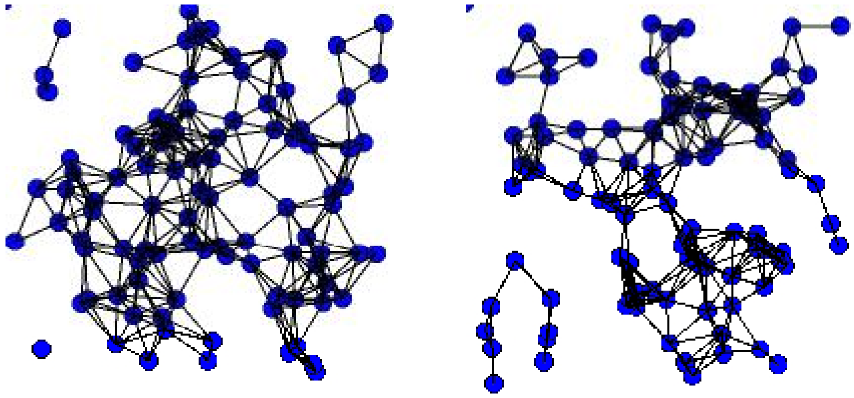
FIGURE 6.13 SELF-POSITIONING SIMULATION RESULTS – CONNECTIVITY (REPRESENTED BY THE POWER RANGE OF ANTENNA) VS. ACCURACY [NUMBER OF MOBILE NODE=100]

A Two-ray ground reflection model is adopted in the simulation, and it is also the default setting in ns2. The receiving power of the antenna is controlled by changing the receiving power threshold which can be counted by:

$$P_r(d) \quad \frac{P_t G_t G_r h_r^2 h_t^2}{d^4 L} \tag{6.2}$$

where P_t is the transmitting power, G_t and G_r is the antenna gain of the transmitter and the receiver respectively, h_t and h_r are the height of transmit and receive antennas respectively, d is the distance, L is the system loss. Usually $G_t = G_r = L = 1$, and $h_r = h_t =$ 1.5m in NS simulation.

In the simulation, there are 100 nodes in a 670x670m^2 area. The range is changed from 90m to 250m, good performance is still achieved, but when the range is changed to 140m, 2 nodes miss their locations; when power range reduced to 120m or 100m, about 16 nodes miss their locations. When a 90m range is used, the number of missing nodes gets even worse, up to 50 out of 100. Figure 6.14 explains the reason. When the power range of antenna is reduced, the nodes are divided into several clusters and isolated from the main cluster.



(a) Simulation Time = 50s
Power Range = 100m

(b) Simulation Time = 200s
Power Range = 90m

FIGURE 6.14 ILLUSTRATION OF THE PARTITIONING ISSUE IN MANET

6.2.2 Comparison of LLBR Simulation Result with Flooding & DREAM

LLBR, DREAM and a typical non-location-based routing protocol, called FLOODING protocol were simulated. The results obtained from LLBR are compared with the ones from the DREAM and Flooding to get some intuitive ideas on its performance based on current algorithms and try to reveal the problems and reasons that deteriorate the performance.

6.2.2.1 Introduction to The Simulation Environment

All the three protocols, LLBR, DREAM and FLOODING were simulated with high data load against both low and high speed of mobile nodes. Table 6.2 lists all the parameters used in simulation.

TABLE 6.2 THE PARAMETERS USED IN THE SIMULATION OF LLBR PROTOCOL

Simulation Time	200s
Simulation Area	300x600m
Number of Mobile Nodes	50
Transmission Range	250m
Movement Model	Random Waypoint
Maximum Average Speed	0-20m/s
CBR Source	20
Packet Payload	64 bytes
Pause Time	10s
Packet Rate	4 packets/s
Traffic Pattern	Peer-to-Peer

Instead of using a square simulation area that is used in the simulation of the Positioning

Algorithm, a 300x600m rectangular area is chosen in the LLBR simulation. The reason is that the rectangular area could give us a long distance of routing path, i.e. the higher hops, which gives us more reasonable simulation results.

In order to focus on the performance of the protocols, the default mobility model in NS2, namely the Random Waypoint mobility model is used to generate the mobile node movement scenarios. The speed of the MN in each movement scenarios between two waypoints is chosen from a uniform distribution with the average value 0.1, 0.2, 1, 5, 10, 15 and 20m/s. The pause time at each waypoint is set to 10 second to maintain a relatively static topology.

The same communication model is used as the model used in [97]. 20 Constant Bit Rate (CBR) sources send 64 bytes packets at a rate of 4 packets per second to 20 destinations. To avoid unnecessary contention of data packets, the transmission time of each transmission is given a 0.0001 second offset. To guarantee the connectivity of the network, the GPS_RATE is set to 0.8.

10 trials on each speed were simulated. The scenario files are generated by NS2 internal program called *setdest*.

6.2.2.2 Simulation Results

FLOODING is the basic protocol used for routing in MANET. It is used as a baseline standard to verity the performance of LLBR and DREAM. In the comparison of LLBR, DREAM and FLOODING, the following performance metrics are used: data packet delivery ratio, average end-to-end delay, average hops for transmitting a data, and average packets generated by network per data packet. The data packet delivery ratio is the number of data packets received by the destinations divided by the number of data packets transmitted by the sources. (In the simulation, there are 1600 packets sent by 20 sources nodes within 20 seconds).

The average hop count is measured by the first data packet which arrives at the destination. In the most of cases, FLOODING has the highest hop counts. The LLBR achieves a better hop count at high speed. The DREAM normally is one-hop better than the others. Both LLBR and DREAM are directional routing protocols, which restrict the packets towards the destination and result in a reduction of non-directional intermediate routing nodes. In the DREAM protocol, the routing area is enlarged as the speed of the destination increases because the higher speed implies larger radius of Expected Zone (See Figure 3.10). So in the higher speed situation, the routing area of the DREAM protocol is expanded and close to the fixed routing area (quadrants with 45° angle in the simulation). This explains the reason that LLBR can have the count of hops with DREAM in higher speed case. The results are shown in Figure 6.15.

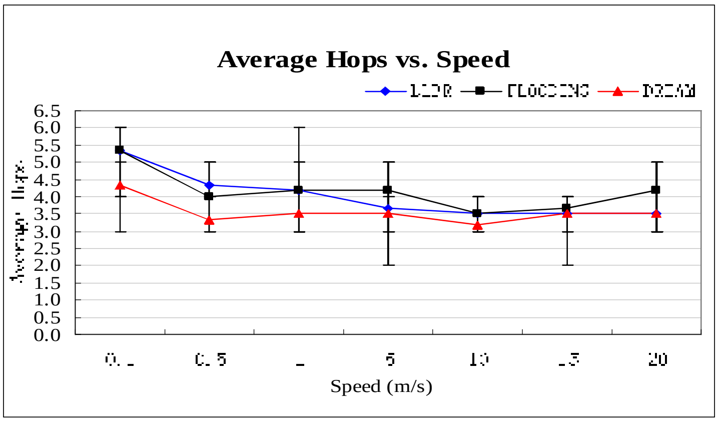


FIGURE 6.15 THE SIMULATION OF LOCATION BASED ROUTING PROTOCOLS - AVERAGE HOPS VS. SPEED

The metric Packets Generated Per Data Packet is also called the number of mobile nodes involved in data routing, or the overhead caused in data routing. Theoretically, the FLOODING needs all the MNs to take part in each data transmission. There are 50 mobile nodes in the simulation, and the result indicates that only 70%-80% nodes actually are intermediate nodes. This is due to contention and congestion in the network caused by high load traffic, which includes positioning packets (the FLOODING protocol simulated in this work is implemented with the positioning algorithm too). Even so, the average packets generated by the FLOODING protocol are still much higher than the other two. When the speed is less than 1m/s, the LLBR and DREAM have the same performance, i.e. about 60% MNs are involved with the data transmission. But if that speed is exceeded, the LLBR protocol functions much better than the DREAM protocol. According to the flooding essence of these two protocols, they should have similar performance on this metric independent of speed. However, the better performance of the

LLBR here is at the expense of lower delivery rate, which will be discussed later in this section. Figure 6.16 shows the results.

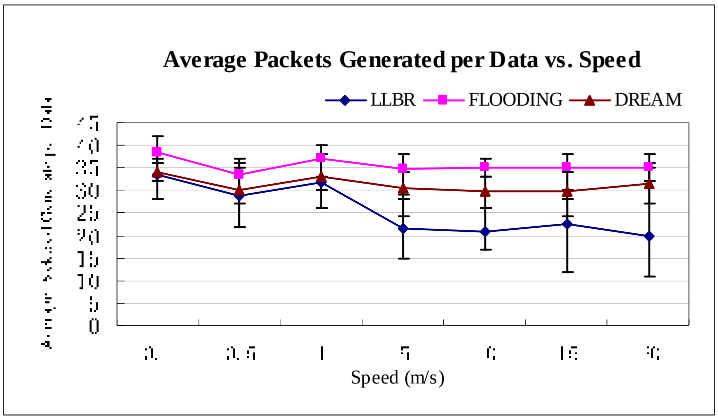


FIGURE 6.16 THE SIMULATION OF LOCATION BASED ROUTING PROTOCOLS - AVERAGE PACKETS GENERATED PER DATA VS. SPEED

The contention and collision also have the influence on the measurement of average packets generated per data packet. Each node is expected to have the location of any other nodes in the network, which means the Direction Indicator is assumed to be always able to be inserted into the data packet. Due to the contention and collision, the Location Packets might not be broadcasted through the network. Lack of the location of the destinations, the source node has to broadcast the data packet to the network, which surely increase the number of the packets generated.

As mentioned before, the performance of LLBR protocol could be influenced by the speed of the destination. Secondly, in the simulation of LLBR, the location update procedure is not performed during the data transmission. Instead, some complementary operation is implemented, such as broadcasting data with limited TTL when exceeding the expected number of hops to enhance the data delivery rate. But these ideas could also introduce higher possibility of collision. Figure 6.17 illustrates the results. In low speed networks, these three protocols perform almost the same and have around 70% delivery rate. When the speed exceed from 1m/s to 20m/s, the delivery rate in LLBR dropps from 70% to 50%, but the DREAM and FLOODING protocols remain at around 75%. Moreover, the DREAM protocol does not contribute to the delivery rate because it can be regarded as a variant of the flooding protocol in the routing area without any link repair mechanisms which are normally used in other non-location-based routing protocols, such as AODV.

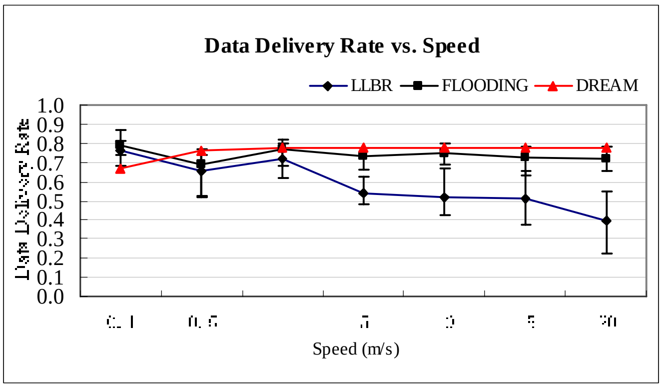


FIGURE 6.17 THE SIMULATION OF LOCATION BASED ROUTING PROTOCOLS - THE AVERAGE DATA DELIVERY RATE VS. SPEED

The End-to-End delay is a very important metric to judge the performance of a routing protocol. The results are illustrated on Figure 6.18 where the LLBR seems not to be working very well as expected. Although the design of the routing algorithm is very similar in LLBR and DREAM, the problem with the LLBR is that its Positioning Stage increases the possibility of the traffic collision. To achieve a richer Location Table in each node, the queue buffer is enlarged in the simulation of LLBR. This means that more packets can be stored in the buffer when collision occurs, but this causes much longer delays as shown in the Figure 6.18.

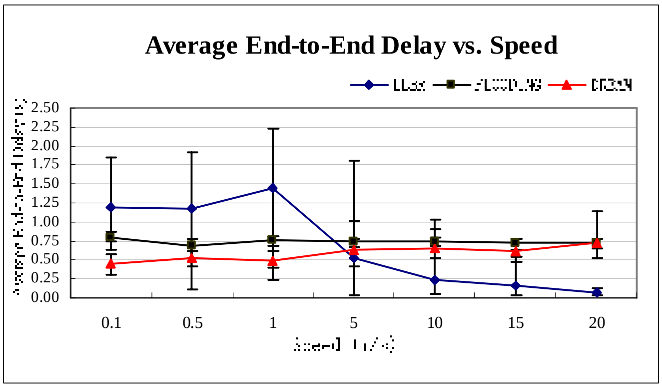


FIGURE 6.18 THE SIMULATION OF LOCATION BASED ROUTING PROTOCOLS - THE AVERAGE END-TO-END DELAY VS. SPEED

The LLBR does not bring a significant improvement on the routing performance compared with the DREAM and FLOODING. There is still much room for improvement and optimization. However, most of location-based routing protocols including DREAM have to rely on the GPS to obtain the location information for each node in the network and GPS signal is not usually stable and accessible in MANET environment, such as in the bad weather, in indoor environment. The novelty of the LLBR protocol brought to the research of location based routing protocol is that it integrates the self-positioning protocols into the conventional routing protocol, and the location information for each mobile node required by the location-based protocols can be acquired even without the aid of GPS. The LLBR can work with the knowledge of the self-generated local coordinates. In other words, a standalone location-based routing protocol is achieved.

In this research, the proposed self-positioning algorithm and LLBR protocol were only simulated with IEEE 802.11b protocol in ns2. They should be able to be used on top of other MAC protocols such as IEEE 802.11g, but the performance might be different and relevant simulations need be carefully studied.

6.3 SIMULATION ON ROUTE MOBILITY MODEL AND HOTSPOT MOBILITY MODEL

A variety of routing protocols have been proposed for the MANET environment. In this thesis, two of the most popular reactive protocols, Dynamic Source Routing (DSR) [66] and Ad hoc On Demand Distance Vector (AODV) [1] are studied in the environments where hotspots and routes exist. DSR uses source routing rather than hop-to-hop routing with the complete route to the destination carried in the head of data packets. AODV is a hop-to-hop routing protocol and can be thought of as a combination of the DSR and a proactive protocol called Destination-Sequenced Distance-Vector (DSDV) [65].

With the existence of hotspots and routes, DSR and AODV are simulated in several different environments. The following important metrics are evaluated for the comparison of their performance.

- *Packet Delivery ratio*: the ratio between the number of packets transmitted by the source nodes and the number of packets received by the destinations.

- *Routing Overhead*: the total number of control packets sent during the simulation by the routing protocols.
- *Average End-to-End delay*: the average time duration the data packets arrive at destinations after they left the sources.

The simulation environments are introduced in next sub-sections followed by the analysis of simulation results.

6.3.1 The Simulation of Hotspot Mobility Model

In this section, the Hotspot model is simulated in two different environments. In order to examine the impact of the environments on the overall routing performance, the same area is used for simulation, but given different configuration to reflect different realistic environments.

A 600x300m area is used to represent the simulation area. The Environment Objects are introduced in Chapter 4 to help describe the real environment; the layout is shown in Figure 6.19 . The environments are configured as Arts Gallery environment and Festival Event environment, respectively.

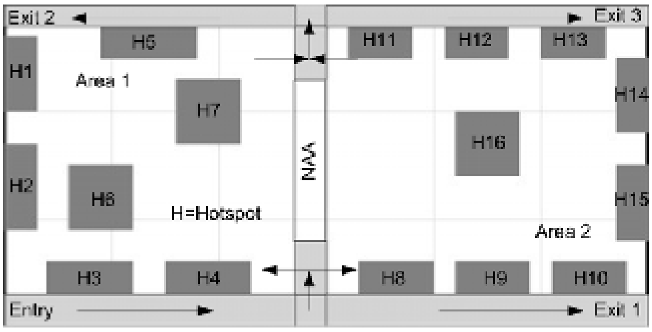


FIGURE 6.19 THE HOTSPOT MODEL SIMULATION ENVIRONMENT

The Art Gallery Environment In this environment, Area 1 and Area 2 can be considered to be two rooms separated by a wall (NAA). All of the art exhibited in the rooms are represented by Hotspots. Visitors enter this area from the entry. They may continue moving to the next exhibition section through Exit 1 or enter either of the two rooms in the exhibition. Once the visitors enter the room, it is assumed that they will move towards the item which they find most attractive then the next most attractive in that room. Note that if the visitor notices that his intended target has too many visitors (up to the capacity of Hotspot), he will slow-down or try other different art. Once they have visited all the objects or if they feel that they have been in the room too long (up to maximum duration allowed to stay in the area), they will leave the room and continue the visit through Exit 2 or Exit 3. In this case, both areas are indoor areas, i.e. Close Area.

The Festival Event Environment Compared to the Art Gallery environment, this environment mostly exists in a public place, such as park so that the two areas can be assumed to be Open Areas. In this case, when mobile nodes move into Area 1 or Area 2 along the same routes described in previous environment, they may just walk around freely for a while then leave. There could be another situation in which some entertainments or shops are distributed inside the areas as hotspots so that the behaviours of the nodes will be similar to the previous ones.

All of the simulations were done using ns2. 40 mobile nodes with 100m omni-direction antenna transmission range were distributed over the simulation area. Considering both environments described in the previous subsection, the Hotspots model was used for the modelling the Art Gallery environment and the random movements that occur in Festival Event are modelled by the Random Waypoint model. The simulations were carried at different average node speeds ranging from 0m/s to 9m/s. At each average speed, the final result is measured as an average of the results from 40 scenarios.

To evaluate the impact of Obstacles on different mobility models, both environments were simulated with Obstacles and without Obstacles. Area 1 and Area 2 were assumed to have a minimum of 15 mobile nodes inside, and the other 10 nodes were distributed randomly along the routes. If these 10 nodes are located inside these two areas, they will stay there for a certain time then leave. If they are located in the Lanes, they will randomly choose a route. The initial snapshot of a simulation is shown in Figure 6.20. For the Random Waypoint model, a 10 second pause time is spent by each node when it gets to a destination and the pause time of the Hotspot model depends on the property of each Hotspot. For the Art Gallery environment, a maximum speed of 7m/s is allowed in the two rooms, but there is not limitation for Festival Event because it is considered to be out-door event. In order to keep the number of mobile nodes constant during the simulation, the nodes that arrive at any of the Exits will appear at the Entry to start a new journey. Each scenario is simulated for 500 seconds.

The measurement is started after the 50 seconds to ensure all the nodes have been distributed throughout the areas. The number of connectivity between any neighbours who can communicate with each other by one hop is calculated every second. The average changes of connectivity at each speed are measured as the metric to evaluate the influence on the network topology caused by the mobility models and the environments.

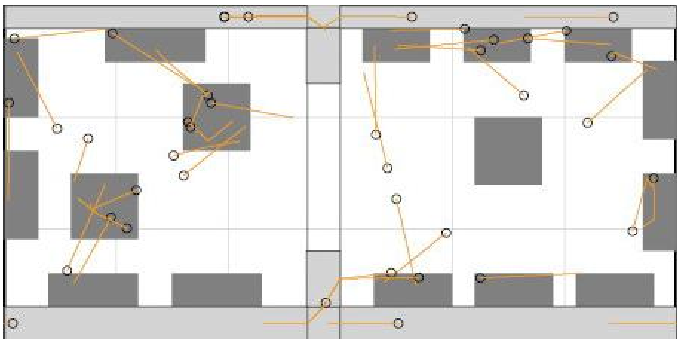


FIGURE 6.20 SNAPSHOT OF THE FESTIVAL EVENT SIMULATION AT THE INITIAL TIME

To evaluate the impact on the routing performance, the AODV routing protocol is simulated. The CBR data packet size is set to 512 bytes and the sending rate is set to 4 packets per second. A maximum of 20 data connection is allowed at one time, i.e. the node can act as either a sender or receiver at any time during the simulation.

6.3.2 Hotspot Environment Simulation Results

As mentioned in Chapter 6, performance evaluation tools are developed in this framework. The Network Topology, i.e. the number of connectivity changes and Routing Performance including data packets delivery rate, number of control packets and data packet end-to-end delay are studied.

Network Topology

In this work, both Hotspot model and Random Waypoint model in the environments with and without the existence of Obstacles are simulated. The results are compared to thoroughly understand the impact on the network topology from the environments.

The average number of connectivity changes with the increasing speed is shown in Figure 6.21. With the existence of Hotspots and NAA, the effective space in the simulation area is highly reduced. Moreover, in the route environment, the movements of mobile nodes are also restricted. With 16 hotspots located in the environment, nodes gathered in one of the hotspots, which generates very high connectivity inside, however as they head for other hotspots this established connectivity is only be maintained for very short time. The Obstacles partition the area into several sub-areas so that the possibility of connectivity loss is increased as the nodes moving in and out of the sub-areas. Obstacles cause higher connectivity change and the Hotspot model normally has a much higher connectivity change than the Random Waypoint mode as the nodes are more distributed throughout the area. An interesting point is that for the Hotspot sub-model the connectivity change without Obstacles increases more sharply than with Obstacles. At higher speed without Obstacles, the frequency of moving in and out of the area is increased and the nodes moving along the routes act like communication bridges to connect the nodes of two sub-areas. On the other hand, the connectivity created by those bridge nodes can not be kept for long at high speed, which increases the change. This explanation can also be applied to Random Waypoint case. In Figure 6.21, it can be found that two curves are jointed at 9m/s and without-Obstacles situation has faster increase. Most of hotspots are located close to the boundaries which are adjacent to the route, therefore more nodes in two sub-areas can be connected and also disconnected by the movement of the bridge nodes. This explains why this effect happen more in the Hotspots environment.

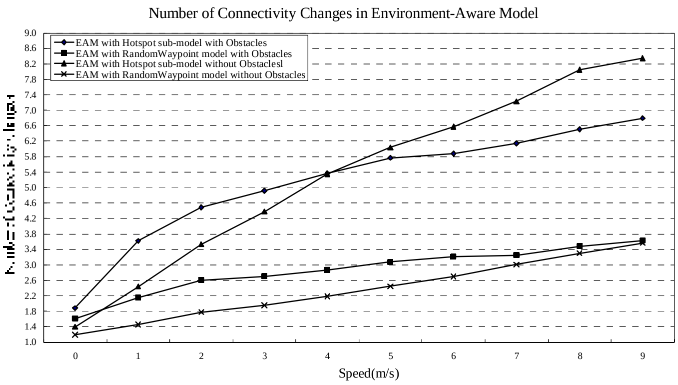


FIGURE 6.21 HOTSPOT ENVIRONMENT SIMULATION RESULTS - AVERAGE NUMBER OF CONNECTIVITY CHANGES

Routing Performance

Both Hotspot model and Random Waypoint model in the environments with and without the existence of Obstacles are simulated.

The data delivery rate measured in different environments is shown in Figure 6.22. Since the Obstacles obstruct the transmission, the mobiles nodes located in different sub-areas are not communicable if there is any boundary of Close Area detected, which obviously deteriorates the delivery rate. The hotspots generate very high density which also causes much higher possibility of collision and packets drop due to the mechanism of the MAC layer of MANET. The delivery rate in both Random Waypoint environments is much more stable than the Hotspots environments. There is a faster drop in the Hotspots model without Obstacles (10% drop) than with-Obstacles (5% drop) and this is due to the network topology change as explained in previous sub-section.

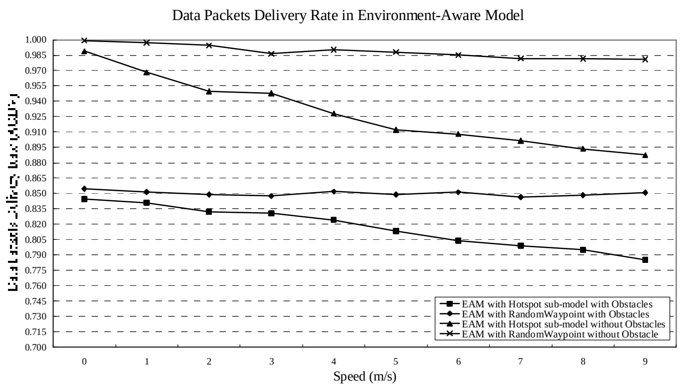


FIGURE 6.22 HOTSPOT ENVIRONMENT SIMULATION RESULTS - DATA PACKETS DELIVERY RATE

The number of control packets sent for routing is plotted in Figure 6.23. This result is highly correlated to the packets reception showed before. Low delivery rate of Hotspots environments causes the nodes to send more control packets to discover the routes as the requirement of AODV.

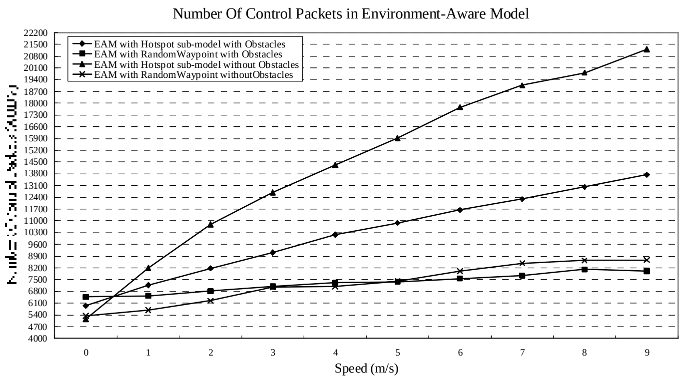


FIGURE 6.23 HOTSPOT ENVIRONMENT SIMULATION RESULTS - THE NUMBER OF CONTROL PACKETS SENT

The high density of nodes in the Hotspots environment causes frequent transmission collision and contention as shown in Figure 6.24. Consequently, the packets are very likely to be delayed until an idle radio channel is found. Due to the higher topology change in Hotspots without-Obstacles environment, the time spent in route discovery is much longer so that the latency of packets transmission is the highest. Random distribution and lowest topology change guarantees that the data packets can be sent and arrive at the destinations quicker in the Random Waypoint environment when no Obstacles exist.

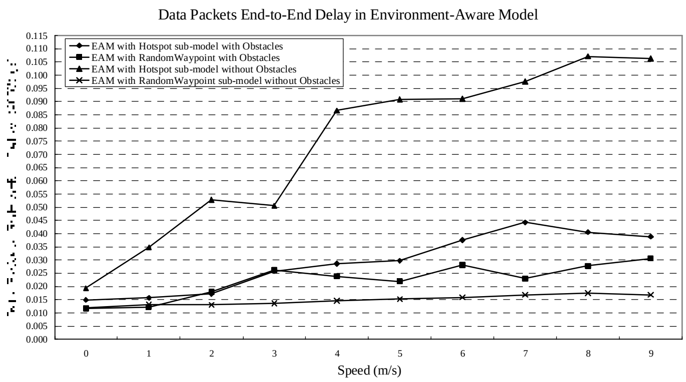


FIGURE 6.24 HOTSPOT ENVIRONMENT SIMULATION RESULTS - THE DATA PACKETS END-TO-END DELAY

6.3.3 The Simulation of the Route Mobility Model

In this section, the simulation of Route model is described. Instead of constructing some virtual environments as the simulation of the Hotspot model, an abstract map is used as the simulation area. A 400x400m area located at the Mappin area of Sheffield, UK and the setting of environment factors are illustrated in Figure 6.25. To clearly observe the influence of movements along the routes, the effect of obstacles described in [98] is not taken into account. The performance of AODV protocol and DSR protocol are evaluated and compared in both Route model and Random Waypoint model. Figure 6.26 demonstrates the simulation at the 15th second.

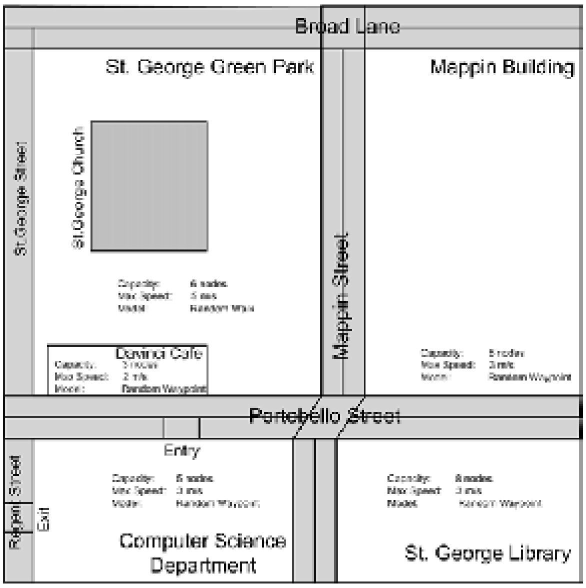


FIGURE 6.25 THE LAYOUT OF SIMULATED MAPPIN AREA, SHEFFIELD, UK

Depend on the different functions of each sub-area, different environmental factors are given. For instance, an internal yard is surrounded by the Computer Science Department building, it gives a space for students to walk around and pass through after the lectures. When nodes enter this area, they will move as Random Waypoint mobility for a maximum of 50 seconds then move out through the exit. The Random walk mobility model is used when nodes are located in the St. George area where the movements are more random and the pause time can be ignored. The metrics are evaluated as the function of average speed of nodes and the function of the total number of nodes simulated. A total of 30 nodes are simulated in all sub-areas and the number is kept fixed for every simulation. The number of nodes moving along the routes is increased from 0 to 50. The average speed of nodes ranges from 0m/s to 9m/s. Note that the speed limit is considered in every sub-area, which implies that the performance impact is only caused by the nodes moving along the routes when the speeds getting higher.

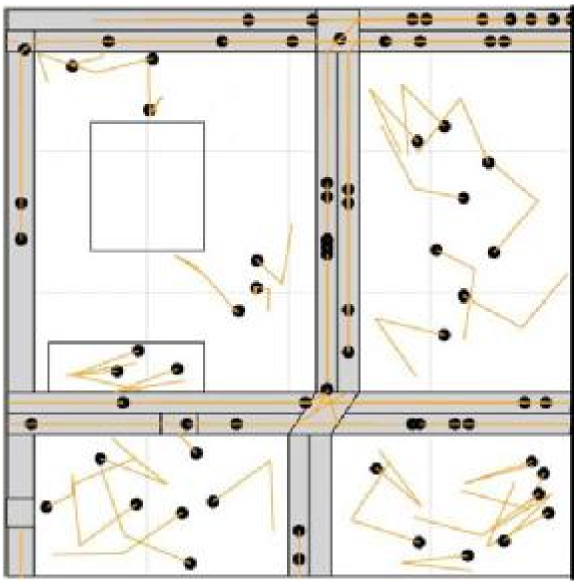


FIGURE 6.26 THE DEMONSTRATION OF THE SIMULATION OF MAPPIN AREA WITH 50 MOIBLE NODES AT 15TH SECOND

6.3.4 Route Environment Simulation Results

The simulation results are shown in Figure 6.27, Figure 6.28, Figure 6.29, performance can be studied as a function of average speed of the mobile nodes. It can been seen that the AODV produces 34% to 64% more routing overheads than DSR with the increase of speed since AODV needs periodically broadcasting HELLO messages to maintain neighbour tables. It is surprising that both protocols have very close packets delivery rate at any average speed, and AODV in this case gives a relatively stable end-to-end delay unlike DSR. It is also interesting to find out that most of the results stabilised when the average speed exceed 5m/s which is set to be maximum speed allowed in all the sub-areas as specified in Figure 6.25. In other words, increasing average route traffic speed has very little effect.

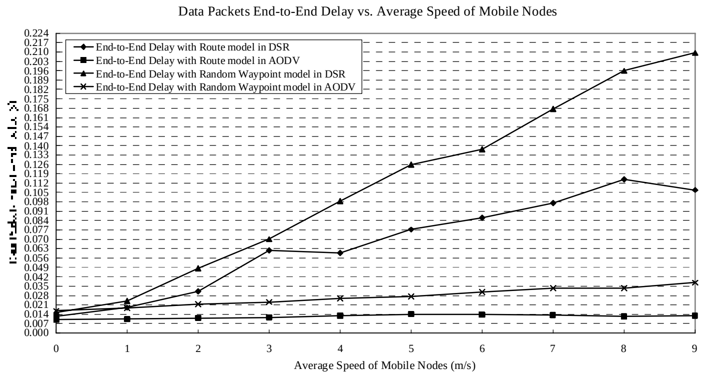


FIGURE 6.27 ROUTE ENVIRONMENT SIMULATION RESULTS - DATA PACKET END-TO-END DELAY VS. AVERAGE SPEED OF MOBILE NODES

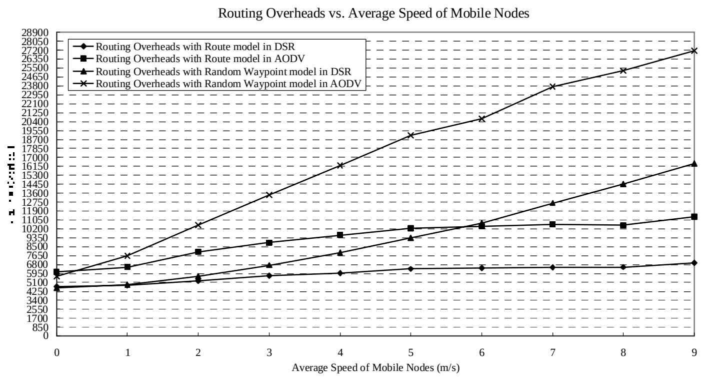


FIGURE 6.28 ROUTE ENVIRONMENT SIMULATION RESULTS - ROUTING OVERHEADS VS. AVERAGE SPEED OF MOBILE NODES

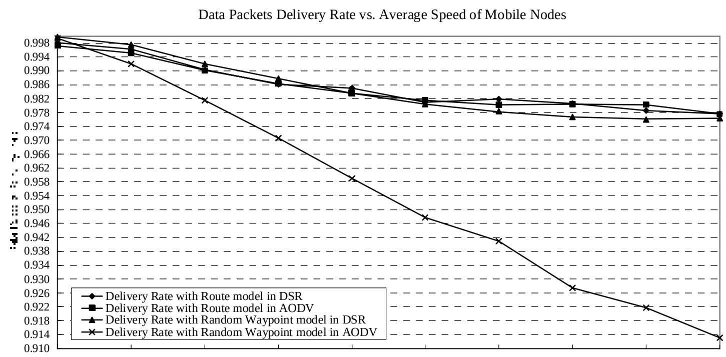


FIGURE 6.29 ROUTE ENVIRONMENT SIMULATION RESULTS - DATA PACKET DELIVERY RATE VS. AVERAGE SPEED OF MOBILE NODES

The performance as a function of the number of nodes is shown by Figure 6.30, , Figure 6.31 and Figure 6.32. Regarding the end-to-end delay, AODV again is relatively stable compared to source routing. It is not surprising to see that the HELLO message mechanism in AODV still produces higher routing overheads than DSR. Note that the Random Waypoint model normally has higher end-to-end delay and routing overheads. The reason is that the network topology is relatively constant in the Route model since most of nodes are forced to be moving in order in routes. There is some slight difference in delivery rate for these two protocols in the Route model. DSR is better when there are less nodes, but starts getting worse when a number of nodes exceed 55. DSR in the Random Waypoint model has slightly better delivery rate than the Route model, which can be concluded that DSR is more suitable for the traffic-like model than hop-to-hop routing since it caches the complete routes to destinations. Compared with Figure 6.29 the delivery rate of AODV is not satisfactory, but it can give a much stable end-to-end delay when the number of mobile nodes is the primary issue rather than the average speed.

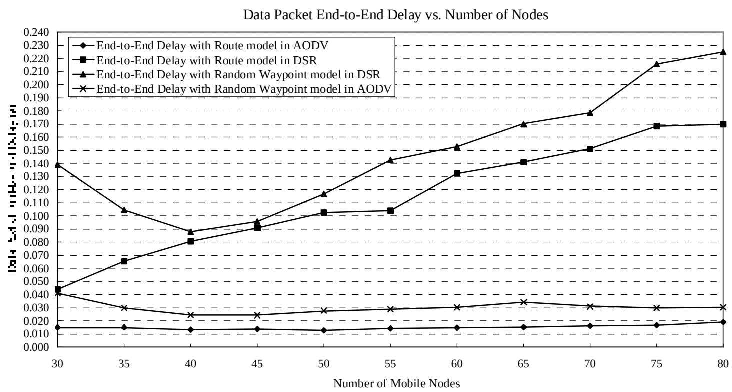


FIGURE 6.30 ROUTE ENVIRONMENT SIMULATION RESULTS - AVERAGE DATA PACKETS END-TO-END DELAY VS. NUMBER OF MOBILE NODES

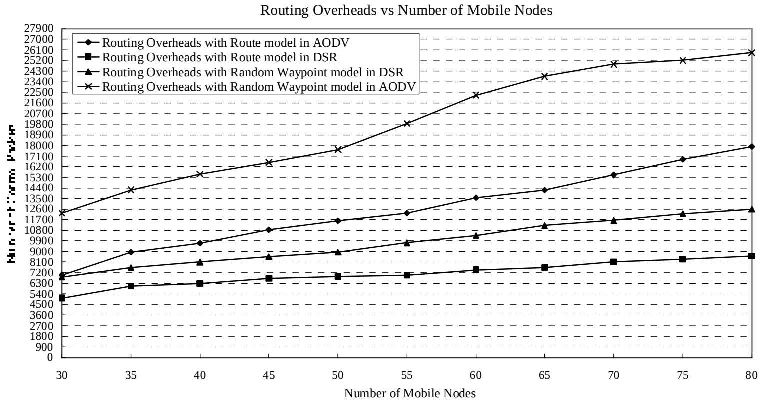


FIGURE 6.31 ROUTE ENVIRONMENT SIMULATION RESULTS - ROUTING OVERHEADS VS. NUMBER OF MOBILE NODES

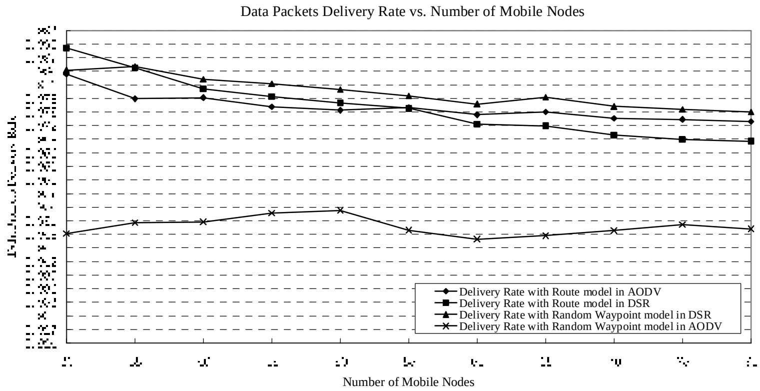


FIGURE 6.32 ROUTE ENVIRONMENT SIMULATION RESULTS - AVERAGE DATA PACKETS DELIVERY RATE VS. NUMBER OF MOBILE NODES

6.4 SIMULATION ON ROADLAMP-AIDED CITY IVC SYSTEM AND BUS-AIDED CITY IVC SYSTEM

Two Inter-vehicle Communication (IVC) systems in the city environment have been proposed in section 4.4.2. The RoadLamp-aided IVC system uses road lamps in the city as the intermediate nodes in order to improve the connectivity of the network; the Bus-aided IVC system assumes that the buses moving in the city are equipped with antenna and are able to improve the communication of the network. In this section, both systems are simulated using the framework introduced in Chapter 5, and the results are also presented.

6.4.1 Graph-based Route Generation and Signal Blocking

The IVC Mobility model is built on the route-associated environment objects, such as Routes, Paths, and Junctions etc. Junction object is used at the point where two environment objects are required to be connected, such as direction change, etc. Therefore, the entire layout of the routes in the simulation environment can be constructed by a graph where the Junction is processed as a vertex and the environment object between the Junctions is abstracted to the edge of the graph. Figure 6.33 gives an example map layout and its resulting graph. The junctions and areas are represented by the vertices of the graph (i.e. $J\{1,...,12\} \rightarrow V\{1,...,12\}$, and $A1 \rightarrow V13$), and all paths between the neighbouring junctions or areas along the route will be represented by the edges. As a path can combine two lanes where the mobile nodes move in opposite directions, the graph is treated as a bi-directional graph.

With knowledge of the graph, routes can be calculated based on different policies. For instance, the route can be picked by given the starting and ending environment objects; it can be also selected by a shortest-path algorithm. A route can also be pre-defined if higher traffic loads in certain paths are required to be simulated (e.g. it can be assumed that certain nodes will use the main streets).

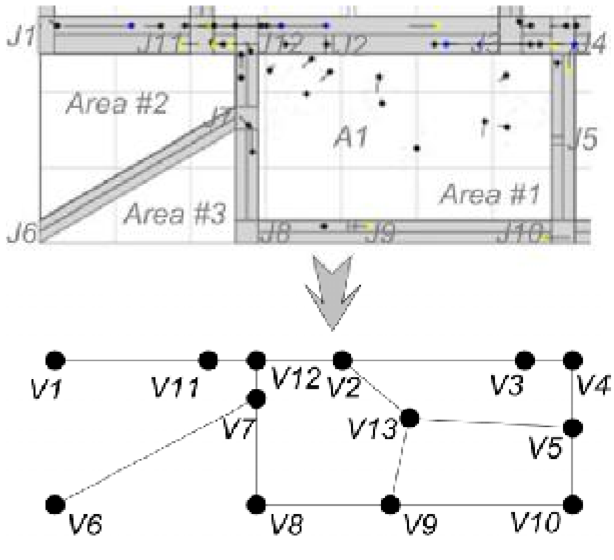


FIGURE 6.33 THE EXAMPLE LAYOUT OF AN AREA AND THE RESULTING GRAPH

As mentioned in section 4.3.4, the signal is completely blocked if there is an obstacle existing in the Line-of-Sight of two mobile nodes. In the City environment, the effect of signal blocking has been reconsidered as follows in order to achieve a more realistic effect:

To simplify the modelling process, if there is an obstacle existing in the Line-of-Sight of two mobile nodes, the power of the signal received will be attenuated in half if the signal is travelling in a FreeSpace environment. More precisely, this effect can be expressed using a mathematical way. If there is an intersection point found between the line connecting the two mobile nodes and the line which presents the border of the obstruction, the signal received by the recipient will only has half power remained than usual case.

6.4.2 Simulation Description

Performance of the routing protocol is evaluated using the ns2 simulator. The Mappin Area of Sheffield, UK is abstracted as the simulation environment whose area is 1000x1000m2. There exist 15 obstacles (buildings) inside this area. Multiple entries and exits are defined in this area, and the node moving out of this area through one of the exits will appear at one of the entries so that the total number of mobile nodes can remain constant. Several main streets are pre-defined. It is assumed that buses can only travel along the pre-defined routes and only the streets along these routes will be equipped with the RoadLamp-aided system. Figure 6.34 illustrates the layout of the simulated city environment.

FIGURE 6.34 THE LAYOUT OF THE SIMULATED CITY AREA

One of the research purposes of this paper is to explore the feasibility of increasing the network performance by utilizing some external help, e.g. using either Bus Nodes (BNs) or Static Nodes (SNs) as ***bridgenodes***. As mentioned before, this performance issue can possibly also be solved by implementing some particular protocols. However, in order to have a better understanding of the impact brought by our proposals, one of the most popular, but location-blind routing protocols, AODV is adopted in our research.

[99] pointed out that it is not worth for the routing protocol to wait for the broken path to be re-connected in an IVC system. Instead, the routing protocol should quickly trigger a path repair protocol to find a new path. The routing mechanism used in AODV is not optimized for the IVC systems, but since it is integrated with some route repair mechanisms, it is believed to be suitable for this environment.

Another research aim is to analyze the influence of both systems in order to conclude which one is better in a certain environment. Therefore, the buses nodes and roadlamp nodes are assumed not to be co-existing in the simulation environment. However, the number of these bridgenodes is kept the same while simulating the two solutions separately.

150 nodes in total are simulated in this city environment. In order to evaluate the impact caused by the number of the bridgenodes, two situations where different amount of bridgenodes (46 bridgenodes and 23 bridgenodes, respectively) exist are considered. 30 pedestrians are introduced in the city area moving at low speed. The Restricted Nodes are mostly located within the area of West Street Green Park in all the simulations. The reason is that inter-vehicle communication is the main focus in this thesis and the effect caused by the nodes located inside the buildings will be trivial since most of the network traffic traveling through buildings will be either weakened or blocked. To give a similar environment, the roadlamps are located along the roads and streets which are bus routes. The main roads such as Portobello Street and West Street are simulated with higher traffic as the result of the bus routes or the roadlamps and traffic lights. The network performance in lower traffic is also taken into account, where the total number of nodes is

reduced to 75 with only 19 bridgenodes and 15 pedestrians. The normal City-IVC system is simulated by replacing all the bridgenodes with High Mobility Nodes (HMNs), i.e. cars. All the routing performance is evaluated with the various average speeds of the HMNs. The average speed is set from 1m/s to 12m/s with step of 1m/s. The detailed settings of the simulations are listed in Table 6.3.

TABLE 6.3 THE SETTING FOR THE SIMULATIONS OF THE CITY ENVIRONMENT

	HMN	LMN	RN	BN	SN
Situation 1					
Number of Nodes	63	30	10	47/0	0/47
Average Speed (m/s)	1-12	1.75	1.5	6	0
Situation 2					
Number of Nodes	87	30	10	23/0	0/23
Average Speed (m/s)	1-12	1.75	1.5	6	0
Situation 3					
Number of Nodes	36	15	10	19/0	0/19
Average Speed (m/s)	1-12	1.75	1.5	6	0
Mobility Model	City-IVC mobility model				
Map Size	1000x1000m^2				
Traffic Model	Maximum 40 CBR connection				
Packet Sending Rate	4 Packets/second				
Data Packet Size	64 bytes				
Simulation Time	500s				
MAC Protocol & Antenna Communication Range	IEEE 802.11b & 150m				

6.4.3 The Simulation Results of Two City IVC Systems

The packet delivery ratio, routing overhead and average end-to-end delay are adopted as the metrics for the comparison of the performance of AODV protocol.

6.4.3.1 Situation One - High Density Mobile Nodes With Large Amount of Bridgenodes

The average end-to-end delay of the packets, the average routing overhead and packet delivery ratio for the three City-IVC systems are given in Figure 6.36, Figure 6.37 and Figure 6.38 respectively. With the lowest delay, the smallest amount of routing overhead and highest delivery rate, the results show a significant advantage of using the roadlamps as the bridges nodes. With large amount of roadlamps, the entire city area can be covered with these Static Nodes with very high percentage. Furthermore, as shown in Figure 6.35 the overlap of antenna range of three SNs (S1, S2 and S3) also guarantees the connectivity among the nodes moving along the route. For example, the communication between ***Car B*** and ***Car A*** still gets bridged by S2 and S1 even if both cars are far apart from each other and there are no other cars in between.

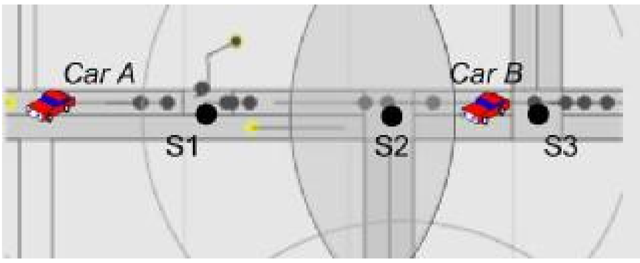


FIGURE 6.35 ILLUSTRATION OF THE ANTENNA RANGE OF STATIC NODES (S1, S2 AND S3) WHICH IS OVERLAPPED

Surprisely, the AODV in Bus-aided City-IVC system does not show an expected better performance than the normal City-IVC system. A number of bus nodes actually introduces higher traffic collisions to the network which causes high delays due to the high possibility of packet queuing. The regular movements of the buses do not contribute to the other two metrics, either. The communication bridged by the bus between the HMNs or LMNs can also get easily lost with the movement of the bus due to the difference of their speed, which would cause high packet lost and high amount of control packets used by AODV.

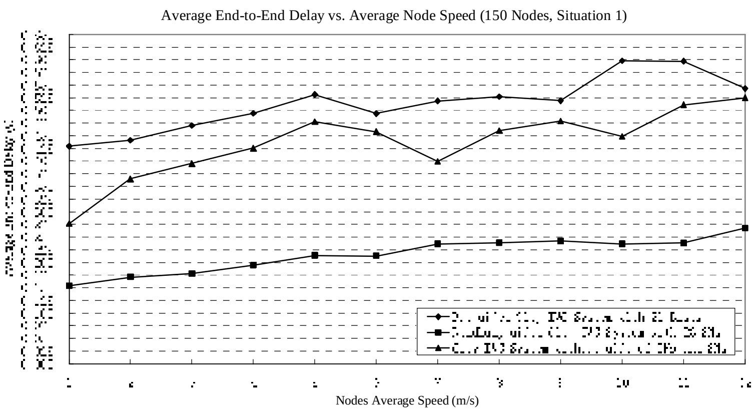


FIGURE 6.36 RESULTS FOR THE CITY ENVIRONMENT SIMULATION ONE - AVERAGE END-TO-END DELAY VS. AVERAGE NODE SPEED (150 MOBILE NODES)

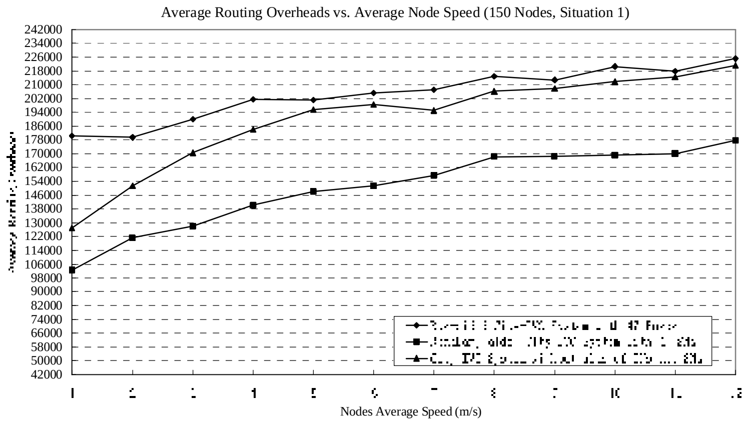


FIGURE 6.37 RESULTS FOR THE CITY ENVIRONMENT SIMULATION ONE - AVERAGE ROUTING OVERHEADS VS. AVERAGE NODE SPEED (150 MOBILE NODES)

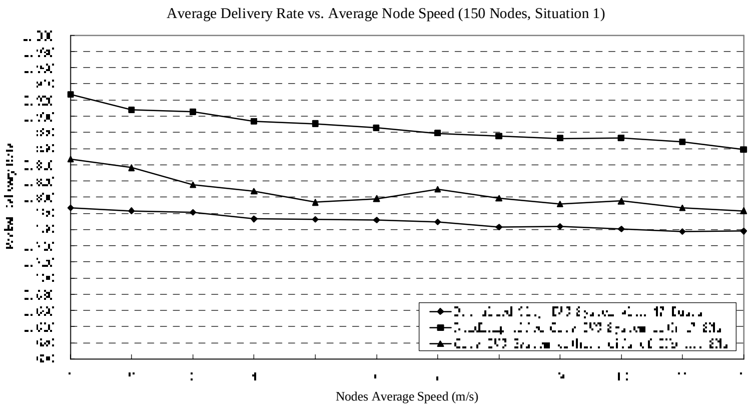


FIGURE 6.38 RESULTS FOR THE CITY ENVIRONMENT SIMULATION ONE - AVERAGE PACKET DELIVERY RATE VS. AVERAGE NODE SPEED (150 MOBILE NODES)

6.4.3.2 Situation Two - High Density Mobile Nodes With Small Amount of Bridgenodes

As shown from the results of situation one, there is no significant difference in the routing performance for the three systems when less bridgenodes exist. The AODV gives slightly better results with the help of SNs. Figure 6.39 illustrates the problem. In situation two, most of the SNs are located at the junctions, i.e. they represent the traffic lights. The average end-to-end delay of the packets, the average routing overhead and packet delivery ratio for the three City-IVC systems are given in Figure 6.40, Figure 6.41 and Figure 6.42, respectively. The existence of these SNs, i.e. the traffic lights can avoid the loss of the links as illustrated in Figure 4.1, but the antenna range of these nodes is no longer overlapped as the case illustrated in Figure 6.35 then the total coverage is reduced, i.e. the ***Car B*** will lose the connection with ***Car A*** when it moves out of the antenna range of T1. Again, a performance change can be found from the results that when the average speed goes over around 6m/s for the Bus-aided City-IVC system compared with normal City-IVC system. However, the AODV gives better performance in this situation when average speed is less than the average speed of buses. This indicates that the movements of Bus Nodes (BNs) can contribute to the maintenance of the connectivity in some cases if the percentage of the bridgenodes to the total number of nodes within the system is low. In the situations where the buses are generally moving faster than the other nodes, the links bridged by them can be easier maintained by the HMNs or LMNs.

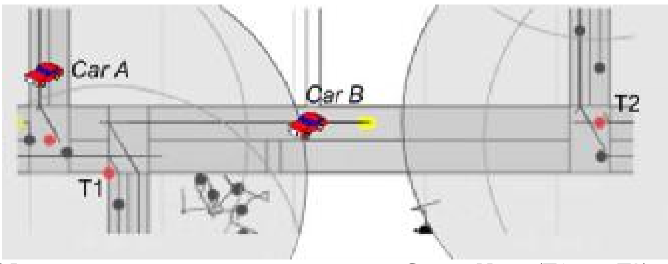


FIGURE 6.39 ILLUSTRATION OF THE ANTENNA RANGE OF STATIC NODE (T1 AND T2) WHICH IS NOT OVERLAPPED

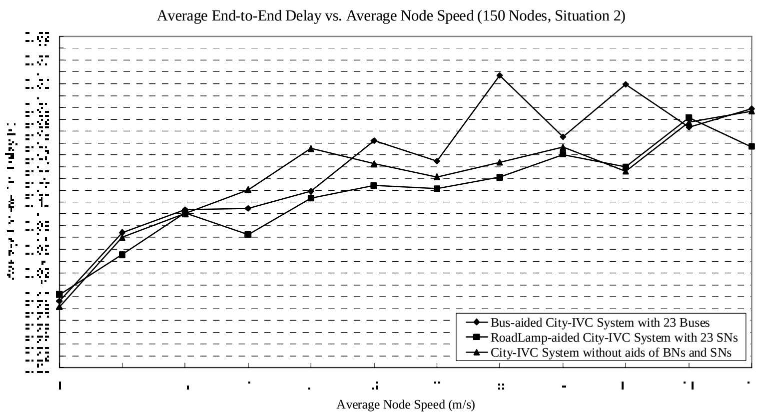


FIGURE 6.40 RESULTS FOR THE CITY ENVIRONMENT SIMULATION TWO - AVERAGE END-TO-END DELAY VS. AVERAGE NODE SPEED (150 MOBILE NODES)

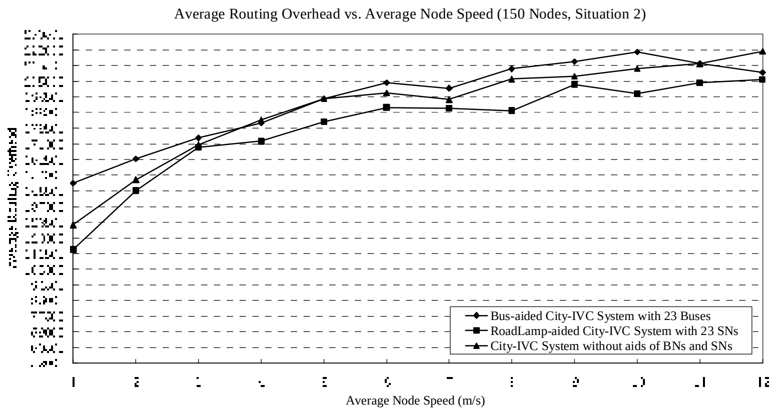


FIGURE 6.41 RESULTS FOR THE CITY ENVIRONMENT SIMULATION TWO - AVERAGE ROUTING OVERHEADS VS. AVERAGE NODE SPEED (150 MOBILE NODES)

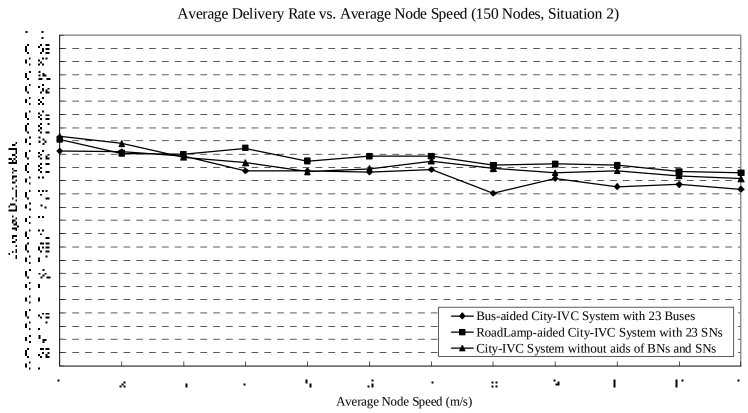


FIGURE 6.42 RESULTS FOR THE CITY ENVIRONMENT SIMULATION TWO - AVERAGE PACKET DELIVERY RATE VS. AVERAGE NODE SPEED (150 MOBILE NODES)

6.4.3.3 Situation Three - Low Density Mobile Nodes With Small Amount of Bridgenodes

In this situation, the total number of simulated nodes is half of what of the previous two situations to evaluate the routing performance under low city traffic. The evaluation of the three metrics is shown in Figure 6.43, Figure 6.44 and Figure 6.45, respectively. The results show more uncertainties in the routing performance. For the end-to-end delay and the routing overhead, the normal City-IVC system gives the worst performance in most of the cases. Less control packets are required for the RoadLamp-aided system because of its relatively static characteristics, but the movements of buses also cause slightly less delay at high average speed (>8m/s). The average delivery rate dramatically drops to about 42% in all systems due to the low density of nodes and the signal blocking effect. The AODV has more or less the same delivery rate, and the best result comes from the normal IVC system and the RoadLamp-aided system is the worst one.

Additionally, compared with the result achieved in situation one, the average delivery rate for the RoadLamp-aided City-IVC system drops down from an average 89% to 82%, but increases from an average of 77% to 79% in the Bus-aided system.

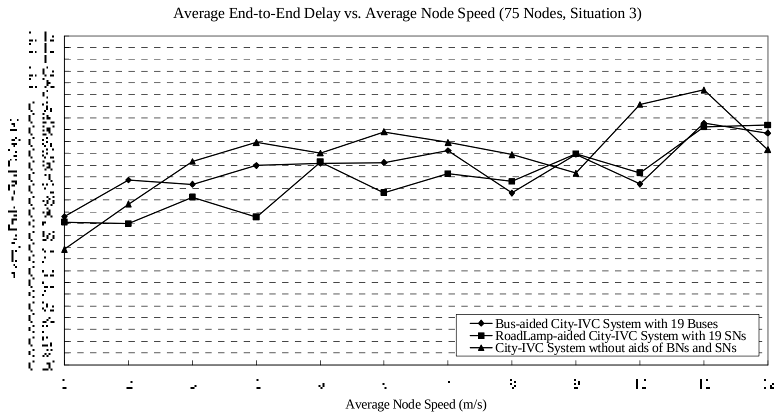


FIGURE 6.43 RESULTS FOR THE CITY ENVIRONMENT SIMULATION THREE - AVERAGE END-TO-END DELAY VS. AVERAGE NODE SPEED (75 MOBILE NODES)

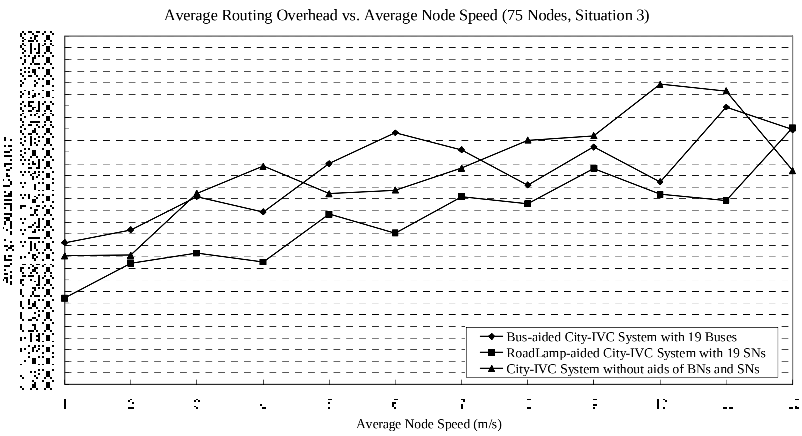


FIGURE 6.44 RESULTS FOR THE CITY ENVIRONMENT SIMULATION THREE - AVERAGE ROUTING OVERHEADS VS. AVERAGE NODE SPEED (75 MOBILE NODES)

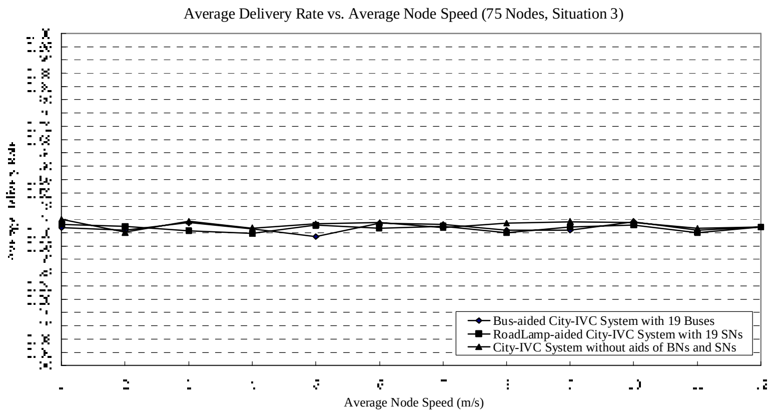


FIGURE 6.45 RESULTS FOR THE CITY ENVIRONMENT SIMULATION THREE - AVERAGE PACKET DELIVERY RATE VS. AVERAGE NODE SPEED (75 MOIBLE NODES)

6.5 CONCLUSIONS

In this chapter the entire research work was evaluated. Three sets of simulations were carried out to evaluate the Self-positioning algorithm and the Location-Label Based Routing (LLBR) protocol, the Hotspots model and the Route model, and two city IVC system, namely the RoadLamp-aided system and the Bus-aided system.

The GPS-free self-positioning algorithm can be used to produce a relative coordinate system by the self-organization of MNs without the knowledge of the network topology. The results show that the accuracy of the calculated coordinate system can reach as high as 100% with the existence of a small number of GPS-nodes. Some factors such as the velocity and the total number of mobile nodes can affect its performance, but this algorithm proved to provide a good positioning solution for MANET.

The self-positioning algorithm can be implemented as a preliminary procedure for routing protocols and location based services. The new Location-Label-Based Routing (LLBR) protocol, a new location-based routing protocol coupled with the positioning algorithm was simulated and also compared it with the DREAM and the FLOODING routing protocols. The result has proved that the implementation of the positioning algorithm is able to give a better performance. However, since the LLBR protocol is still a prototype version, the results shows it still has some weaknesses such as long end-to-end delay. These disadvantages are pointed out and thoroughly discussed.

The impact caused by the introduction of the Hotspot mobility model and the Route mobility model on the performance of the protocols is studied by the evaluation of three metrics, end-to-end delay, delivery rate and routing overheads for two routing protocols, DSR and AODV. The results have shown that the number of hotspots may have a significant influence on the routing performance. Moreover, DSR is considered to be the best choice with higher packets delivery rate and less routing overheads.

Furthermore, a complex environment, the Sheffield Mappin area is constructed in order to show the flexibility of the Route model. The results show the DSR has better routing performance in the city area if the traffic increases or the average speed of the traffic is increased.

The performance of the conventional protocol AODV is intensively evaluated in two proposed systems, RoadLamp-aided City-IVC system and Bus-aided City-IVC system, and compared with the normal City-IVC system. The simulation results show that the routing performance of AODV can be enhanced to some extent by the introduction of the SNs as the bridgenodes, and the advantage is quite significant if a larger number of SNs is used. As per the Bus-aided City-IVC system, the conclusion in [80] does not always held. There is a trade-off between the network performance and the number of the BNs. A large amount of BNs can cause higher packet collision which devastates the performance, and the performance is enhanced when the average speed of the cars is low, i.e. when the cars are generally moving slower than the buses if the number of buses is decreased. In the low node density city environment, there are still advantages to be gained by utilizing the bridgenodes if the end-to-end delay and routing overhead are considered as important. However, both of the two special systems can not guarantee better delivery rate in such situation. The results prove that inter-vehicle communication can be enhanced by taking advantage of special nodes, such as Static Nodes (SNs) and Bus Nodes (BNs) in the city environment without implementing the optimized routing protocols and the results also indicate that the situation in which both systems are deployed can be critical and needs evaluation. This can only be done with the aid of the framework proposed in Chapter 4 and Chapter 5 of this thesis.

Chapter 7 MOBILITY-CONCERNED EMULATION OF MOBILE AD HOC NETWORKS

7.1 INTRODUCTION

Besides simulations, emulations have also become a popular method in the research and development of mobile ad hoc network protocols and software. Unlike the simulations which usually use a set of scenarios and a simulation system in order to obtain some data for the analysis of the target environment, the emulations incorporate real hardware or softwares into the synthetic environment in a controlled manner. Therefore the experiments in the emulations are expected to highlight some issues which can not be discovered by simulations alone [85] [86].

This chapter describes how the environment-aware framework for the simulation of mobile ad hoc networks can be expanded into a network emulator.

7.2 RELATED WORKS

Several emulators have been developed in the research of mobile ad hoc networks. MobiNet [88] is one of the best. It provides a scalable emulation infrastructure for a mobile ad hoc network. It utilizes a cluster of emulator nodes to appropriately delay, drop or deliver packets in a hop by hop fashion based on MAC-layer protocols, ad hoc routing protocols, congestion, queuing, and available bandwidth in the network. However, the emulation of the mobility is weak in MobiNet. It only supports the simple Random Waypoint mobility model and also lacks of functionalities to construct and visualise a complex environment. The NTRG stack [87] proposed by Network and Telecommunications Research Group of Trinity College, Ireland is a flexible communications stack created to provide a testbed for mobile wireless networking on a range of devices. The layered structure of the stack allows the user to insert, remove and replace layers in the stack dynamically. JEmu wireless network emulator [87] is built on the NTRG stack and provides a client/server style emulation: each client has a radio emulation layer of NTRG to connect to an emulator server. However, the main issue with JEmu and most of other emulators such as Emwin [89] is the scalability. For example, it is very difficult for them to plug in a new routing protocol.

Emulation is the intermediate stage between the simulations and the final deployment of the networks. Lots of simulations have been done in our research and the framework of mobility-concerned simulation is also a key work for this thesis. In this section the initial work to create a mobility-concerned emulator is described. Using the emulator, the mobile ad hoc networks with different protocols can be emulated, and the mobility and the environment information can be also taken into account. New computer technology, such as JBoss technology will be used to enhance the capability and scalability of the emulator too. The design is described here and more research is required in future work.

7.3 THE DESIGN OF THE LAYERS FOR THE EMULATED AD HOC NETWORKS

Similar to the Open Systems Interconnect (OSI) model [90] which divides a Local Area Network (LAN) into seven processing layers, the layers for the emulated mobile ad hoc networks are also designed in our work. Each layer has a specific purpose and functions independently of the other layers. However, like the layers in OSI model, each layer here is also aware of its immediate upper and lower layers.

Figure 7.1 demonstrates the design, and the detailed explanation of each layer is now given:

- **NIST/Net Network Emulation -** In order to emulate the condition of the wireless physical layer, the NIST Net network emulator [91] is used. The *NIST Net* network emulator is a general-purpose tool for emulating performance dynamics in IP networks. The tool is designed to allow controlled, reproducible experiments with network performance sensitive/adaptive applications and control protocols in a simple laboratory setting. By operating at the IP level, NIST Net can emulate the critical end-to-end performance characteristics imposed by various wide area network situations (e.g., congestion loss) or by various underlying sub-network technologies (e.g., asymmetric bandwidth situations of xDSL and cable modems);

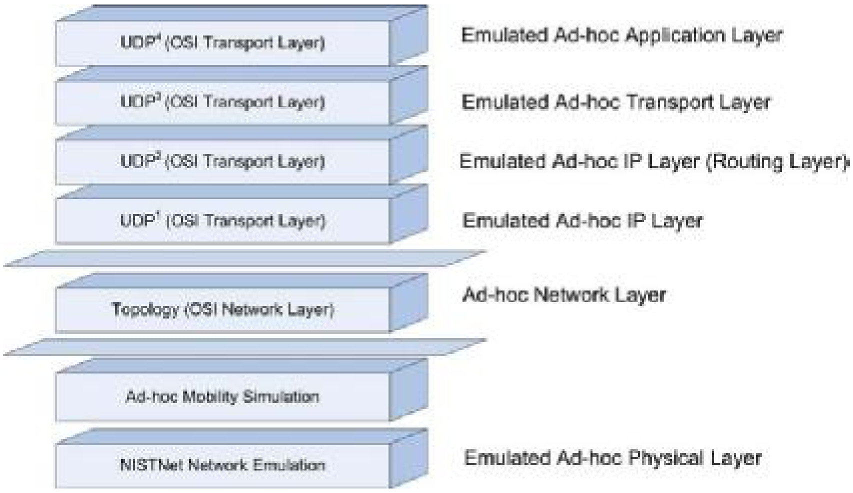


FIGURE 7.1 THE DESIGN OF THE LAYERS FOR THE EMULATION OF MOBILE AD HOC NETWORKS

- **Ad-hoc Mobility Simulation** – The mobility model is being modelled in the server to simulation the mobile node movement. At the initial stage, the locations will be assigned randomly and updated with real-time according to the models. The server decides the link-status between any two nodes based on the calculation of simulated distance. The movement of mobile nodes along with the environment where the network will be deployed will be demonstrated by the aforementioned visualisation tool;
- **Topology** –Client/Server architecture is adopted in this design; Figure 7.2 demonstrates the topology;
- **User Datagram Protocol^1 (UDP^1)-** Emulate the IP datagram; Example fields included in the datagram: Source_IP_Address, Destination_IP_Address;
- **UDP^2 -** All the routing-specific information is encapsulated in the UDP datagram. Since all the traffic is routing through the server, it will be the routing decision maker on behalf of any node according to the routing protocol; In case of LLBR protocol, the fields included in the LLBR-Positioning datagram could be the Rotation_Angle, Offset_X, Offset_Y etc.; the LLBR-Location datagram should contain the Node_ID, Node_Location_Status, Node_Location etc; the LLBR-Routing Packets will contain the Direction_Indicator;
- **UDP^3** - Emulate the OSI Transport Layer packets (e.g. TCP…);
- **UDP^4 -** Emulate the OSI Application Layer packets;

7.4 THE PROPOSED EMULATION TESTBED

As illustrated in Figure 7.2, the CenterNode, Mobility Simulation Server and multiple nodes are three key components in this design. The Mobility Simulation Server represents the framework of the mobility-concern simulation. By taking the advantage of the serialisation of the MNMovementSegment and MovingPath objects mentioned before, the resulting .ser files can be loaded into the CenterNode so that the CenterNode can have overall knowledge of the mobility of each mobile node. The integration of the simulation framework brings the complex environments and scenarios to the emulation experiments. The CenterNode is central controller of the testbed. Each node connected to this testbed represents a mobile node, and any communication between any two nodes has to travel through the CenterNode which decides on the connectivity of the nodes according to its mobility data. The CenterNode can also remotely control the nodes, for example, start or stop the operation of the node if needed. With the help of SVG and the visualisation tools developed in the simulator, the emulated network can also be monitored from the CenterNode.

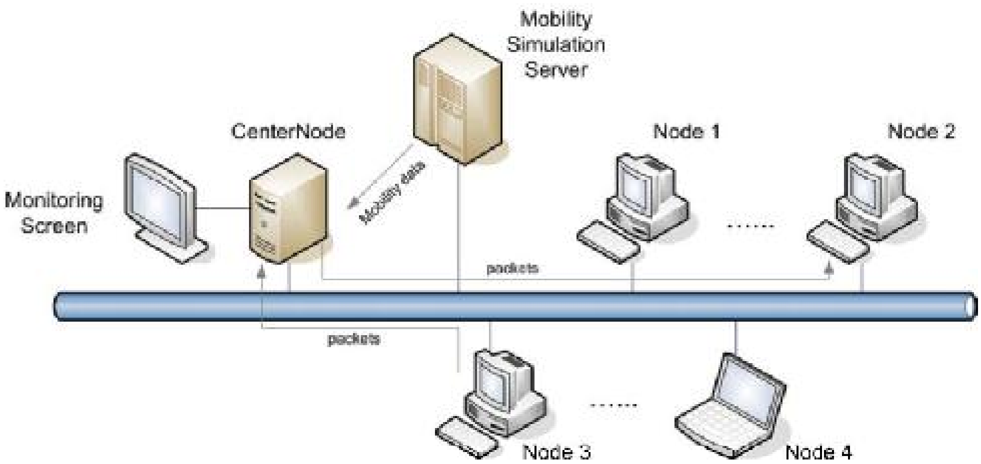


FIGURE 7.2 THE DESIGN OF THE TESTBED FOR MOBILITY-CONCERN EMULATION

7.5 THE SCALABILITY OF THIS EMULATOR – THE JBOSS TECHNOLOGY

The JBoss Application Server (JBoss AS) [92] is adopted for the implementation of this emulator. JBoss AS is a Java 2 Platform Enterprise Edition (J2EE) [94] based free and open source software. It can be running on numerous operating systems including

Windows, many POSIX platforms, and others, as long as a suitable JVM is present, which enables the Node shown in Figure 7.2 to be many type of computing equipments. JBoss AS also supports Cluster technology. By definition, a computer cluster is a group of tightly coupled computers that work together closely so that in many respects they can be viewed as though they are a single computer [93]. Both CenterNode and Nodes are running the JBoss AS and also configured into the same cluster. i.e. become the cluster nodes. The protocols and applications emulated are running locally in each cluster node. The advantage is that if the new or updated version of protocol is deployed into one cluster node (in this work the Center Node is always the first node for new deployment), this new deployment will be automatically pushed into the network and deployed into other running cluster nodes. Therefore, the emulated mobile ad hoc networks can be easily updated whenever there is new version of the protocols and applications available in each layer.

With these outstanding features and the power of other J2EE technology, the emulator becomes very scalable to integrate other works, such as new routing protocols from the third party.

7.6 CONCLUSIONS

In this chapter, the design of a new emulator is described. By taking advantage of the framework described in the previous chapter, the mobility and the environment information can be taken into account in the emulation of mobile ad hoc networks. The serialisation files can be uploaded to the emulator and processed by each computer node which represents the individual mobile node, thus the mobility of mobile nodes in the environment can be aware of during the emulation. The network layers for the emulated mobile ad hoc networks and the testbed are designed and described. As there might be many mobile nodes to be emulated, JBoss technology is adopted into the design to enhance the scalability of this emulator.

In the emulator, the wireless environment can be emulated and the packets sent by the nodes are transmitted through the real network. Only the design of the emulator is presented in this chapter, its implementation is still under development. JBoss technology is a key knowledge used in this emulator. Since it has been heavily used in an industrial project we are involved: Multimedia Messaging Service server platform [95], it is believed that the design will lead to a successful implementation and more accurate results are expected

Chapter 8: CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORKS

8.1 THE CONCLUSIONS OF THIS THESIS

This thesis has studied the routing performance issues of mobile ad hoc networks and the impact of mobility of mobile nodes by introducing a new location based routing protocol along with a novel self-positioning algorithm and a new environment-aware mobility model with a framework focusing on mobility-concerned simulation.

Mobile ad hoc networks have been a hot research area for some years. This area has a very broad range of topics worth being discussed. The radio specification, the energy consumption, the antenna performance, the mobility of mobile nodes, the protocols such as routing protocols, and the network topologies and so on, all these topics are related to the mobile device, namely the mobile nodes. Chapter 1 gave a comprehensive review of all these topics plus some very mobile device specific ones such as the physical and environmental issues, self-organisation characteristics and even the fashion factor of mobile nodes. From the mobile node's perspective, the mobile ad hoc networks are re-discovered, which gives a thorough background of our research and also makes a nice explanation of the motivation and the importance of our work.

A new positioning algorithm for the mobile ad hoc networks was presented in Chapter 3. It shows that an independent local coordinate system can be produced by the self-organization of the mobile nodes without the knowledge of the network topology. It also shows that this method can operate well with partial or even complete absence of GPS information. Two neighbouring GPS-nodes are enough to provide all nodes in the network with high accuracy GPS positions. This method is simulated and the results show that the accuracy of the calculated coordinate system to the real GPS system can reach as high as 100%, with a relatively small number of GPS-nodes existing in the network. Furthermore, based on this algorithm, a new location based routing protocol called Location Label Based Routing (LLBR) was also proposed and simulated. The self-positioning algorithm is used as a preliminary procedure of this proposed routing protocol in order to generate the location for each mobile node. The location of each mobile node is broadcasted into the network so that the other nodes can aware of it. A location label which indicates the direction of the destination node is inserted into each data packet. The intermediate node makes the decision whether or not it should forward this incoming packet according to its location related to the destination. The simulation results show that LLBR can improve the routing performance to some extent. However, In the case of high mobility, the performance of the self-positioning and the LLBR protocol can be significant reduced due to the partitioning of the network and the dynamic change of the network topology.

From the study in Chapter 3, it was realized that the mobility of mobile nodes is the one of the critical factors to impact on the network performance. In the research of mobile ad hoc networks a mobility model is usually used to simulate the movement of the mobile node. However, this is not adequate as it does not actually consider the environment in which mobile nodes operate. In Chapter 4, as a part of the environment-aware framework in this work a new mobility model, called Environment-Aware Mobility (EAM) model is proposed. This model enables the integration of current existing models and new models to be used in complex environments where mobile nodes are deployed. Scalable Vector Graphics (SVG) is used for the design of the layout of the environment. Some abstract Environment Objects (EOs) were introduced to represent the various areas existing in the networks. The research has shown that the movements are highly influenced by both intrinsic characteristics and some properties of the EOs. The behaviours of the mobile nodes are not only dependent on which mobility models they use but also on the area in which they are located. The signal-obstruction effect is also incorporated in this model with the introduction of the Open or Closed properties of the EOs. The signal is blocked if the transmission needs to go through any boundary of the Closed EOs. Simulations were done with different mobility models given the same geographical layout of network but with different environmental configurations. The scenarios were able to be visualized on demand in order to study the performance of the network in depth. The average connectivity changes were measured and the throughput, end-to-end delay and delivery rate of AODV routing protocol were evaluated. The results prove that both the network topology and the performance of the protocols are significantly influenced by the mobility models and the environmental factors.

Two variant of EAM models were introduced and used in the framework, namely the Route mobility model and Hotspot mobility model in order to model the mobility observed in some particular environments. Hotspot mobility model is capable of describing the environments where attraction places exist. In these models, the next destination of the mobile node can either be another hotspot or an arbitrary point inside the entire simulation area, depend on the status of the hotspots and the strategy that the node is using. With the capability of integration with other conventional model, the Route mobility model can be used to give a more precisely construction of a complex environment, such as a city area, a highway traffic, etc. The impact on the performance of the protocols is studied by the evaluation of three metrics, end-to-end delay, delivery rate and routing overheads for two routing protocols, DSR and AODV. The results have shown that the number of hotspots has a significant influence on the routing performance. Moreover, DSR is considered to be the best choice with higher packets delivery rate and less routing overheads. Furthermore, a complex environment, the Sheffield Mappin area was simulated in order to show the flexibility of the Route model. It is very interesting to see that the DSR has better routing performance in the city area if the traffic increases or the average speed of the traffic is increased. Both the Hotspot model and the Route model are good candidates for modelling realistic MANET environments. However, more works needs to be carried out towards this direction. In the Route model, the influence caused by different strategies on the protocol performance needs to be further studied. In the current version of the Route model, the routes are randomly chosen by the nodes. Some intelligence, such as the capability to find the shortest route and the optimum route needs be added to the Route model and a larger area needs to be studied.

Wireless communication plays an important role in our life. In the future, most of the vehicles and pedestrians in the city area will be involved with all sorts of wireless communication. The resulting network can be considered as an Inter-Vehicle Communication (IVC) system with the characteristics of a mobile ad-hoc network. The city environment also introduces some extra factors which bring more uncertainty on the network performance. The characteristics of the movements of mobile nodes in these environments are very different; the signal blocking effect could be very significant due to the large numbers of buildings; the possibility of confliction and collision in the data transmission might be very high since all the cars are forced to drive together along the road. It was shown that by using the node heterogeneity the network performance can be enhanced with no special routing protocols involved. The research proved that performance can be improved by utilizing special Static Nodes and Bus Nodes. The performance of the conventional protocol AODV was intensively evaluated in the RoadLamp-aided City-IVC system and the Bus-aided City-IVC system, and compared with the normal City-IVC system. The simulation results show that the routing performance of AODV can be enhanced to some extend by the introduction of the SNs as the bridgenodes, and the advantage is quite significant if a larger number of SNs is used. As per the Bus-aided City-IVC system, the conclusion in [80] does not always held. There is a trade-off between the network performance and the number of the BNs. A large amount of BNs can cause higher packet collision which will devastate the performance, and the performance can be enhanced when the average speed of cars is low, i.e. when the cars are generally moving slower than the buses if the number of buses is decreased. In the low node density city environment, there are still advantages to be gained by utilizing the bridgenodes if the end-to-end delay and routing overhead are more concerned. However, both of the two special systems can not guarantee better delivery rate in such situation. The results prove that inter-vehicle communication can be enhanced by taking advantage of special nodes, such as SNs and BNs in the city environment without implementing the optimized routing protocols, and the results also indicate that the situation in which both systems are deployed should be seriously considered since the performance can otherwise be very poor.

New mobility models, the Route Mobility Model and the Hotspot Mobility Model were given in Chapter 4 and two IVC systems in the city environment were proposed and discussed in the same chapter. These models needed to be simulated and evaluated, unfortunately, with current existing tools, this can not be possible. In Chapter 5, a new framework was developed. This framework includes a new mobility modeller for mobile ad hoc networks. This modeller can be used well for modelling the conventional mobility models and new models, but more importantly, it can also model the environment where the networks are deployed by introducing SVG to represent the environment object. By taking the advantage of the animation features of SVG, a tool for visualizing the mobility of mobile nodes and the changing of the network topology was also developed in this framework. The mobility information generated by the framework can be fed to the ns2 simulator for network simulation. A set of evaluation tools is also included for the measurement of both connectivity-related metrics and routing-related metrics. The framework is designed with the concern of scalability. Other researchers can take the advantage of the structure of this framework, including the generic mobility model, environment design and configuration, measurement tools and so on for research of their mobility models for particular environments.

The set of tools introduced in the framework is used for simulation and evaluation and the methodologies and results of the entire research are presented and discussed in Chapter 6. Three sets of simulations were carried out, Self-positioning algorithm and Location-Label Based Routing (LLBR), Hotspots model and Route model, and two city IVC system, RoadLamp-aided system and Bus-aided system. The framework described in Chapter 5 is used for simulation and also evaluation.

The technology of Serialisation was used into this framework. The mobility information of each mobile node was serialised into files which can deserialised later for other purposes, which allows the framework aims for simulation can be expanded to emulation. The network emulator is introduced in Chapter 7. The serialisation files can be uploaded to the emulator and processed by each computer node which represents an individual mobile node. In the emulator, the wireless environment can be emulated and the packets sent by the nodes are transmitted through the real network cable. JBoss technology is adopted in order to enhance the scalability of this emulator. By the emulation of the mobile ad hoc network, more accurate results of evaluations are expected. The design of the emulator is done, but the implementation has not been finished.

It can be concluded that the objectives of this thesis introduced in Chapter 1 have been reached.

8.2 ORIGINAL CONTRIBUTIONS OF THIS THESIS

The contributions of the thesis can be outlined as follows.

- A thorough study of mobile ad hoc networks is provided. The properties of mobile nodes are reviewed to give a detailed background of the research area.

A new decentralised algorithm enables the mobile nodes in the mobile ad hoc networks to compute their locations without the help of the GPS. This self-positioning algorithm is capable of generating a local coordinates system and let each mobile node compute its own coordinate in this system. The great novelty is that if part of the network can receive the GPS signals, the mobile nodes that have no access to the GPS can use this algorithm to convert the locations in local coordinates to the location in GPS system. This feature can potentially contribute to many existing location based services and extend their services into GPS-free environment, such as indoor networks.

- A new location based routing protocol that integrates with the new positioning algorithm was proposed, called Location-Label Based Routing (LLBR) protocol. This new routing protocol essentially takes advantage of the locations of mobile nodes to optimize the routing of data packets. Unlike other location based routing protocol such as DREAM and LAR which are depended on the GPS system for the acquisition of the location, this LLBR protocol fully integrates the self-positioning algorithm, use the resulting local coordinates system and insert a location label to indicate the direction of destination to reduce the routing area, i.e. only the mobile nodes reside in the same direction to the destination node with the source node can possibly be involved in the packet forwarding.

A new concept of mobility modelling is proposed which not only takes into account the characteristics of the movements of mobile nodes but also the impact on them from the environment. To support this proposal, a novel realistic mobility model, Environment-Aware Mobility (EAM) model is developed with the feature of incorporation with the environments where the mobile ad hoc network is deployed.

The movements of the mobile nodes are not only decided by themselves but also restricted to the environment they are located. The real environment is carefully studied and modelled into some basic so called Environment Objects, such as the lane, route, hotspot etc. Like the real world, these environment objects have different restriction and characteristics to influence the mobility of mobile nodes, which are implemented into the new mobility model.

- By taking the advantages of the EAM model and also to demonstrate its scalability, two variant models, Route Mobility model and Hotspot Mobility model are proposed. The Hotspot model is capable of describing the environments where attraction places exist. In this model, the next destination of mobile node can either be another hotspot or an arbitrary point inside the entire simulation area, depend on the status of hotspots and the strategy the node is using. With the capability of integration with other conventional model, the Route model can be used to give a more realistic construction of a complex environment, such as city area, highway traffic, etc.
- Node heterogeneity is studied for the Inter-Vehicle Communication (IVC) system in the city environment. Five types of nodes, High Mobility Nodes, Low Mobility Nodes, Restricted Nodes, Bus Nodes and Static Nodes are described for better understanding the IVC mobile ad hoc networks in city environment.
- Two suitable systems are proposed to improve the performance of the Inter-Vehicle Communication (IVC) system in the city environment by introducing two new special IVC systems, i.e. the RoadLamp-aided IVC system and the Bus-aided IVC system. The RoadLamp-aided IVC system uses the static nodes such as roadlamps and the traffic lights in the city as the bridgenodes that are involved with the packet forwarding to increase the connectivity of the network. The Bus-aided IVC system assumes the buses are equipped with the antennas. By taking the advantage of the regular movement of the buses, the communication between other mobile nodes can be improved.

An Environment-Aware framework for the research of mobile ad hoc networks was designed and implemented. This framework not only includes the new EAM model but also contains a set of tools for mobility modelling, environment construction, mobility monitoring, metrics measurement, and also provides a configurable and scalable architecture which can be a great contribution to other research in mobile ad hoc networks.

A new mobility modeller is included in this framework. This modeller can not only be used for modelling conventional models such as Random Waypoint model, Random Direction model etc and the group model RPGM model, but also enhance the models by introducing environment information, i.e. Environment Objects to present a complex realistic environment.

- SVG was used throughout the framework. The basic shapes defined in SVG were used for the environment construction; the animation features supported by SVG were used for visually monitor the movement of mobile nodes during the simulation; the movement scenario generated by ns2 can also be used in an animated SVG file for further study.

The mobility information can be fed into ns2 network simulator. Therefore, more valuable information can be learned from the network simulation using ns2 as more realistic environment have been taken into account.

- The framework provides a set of evaluation tools. Two types of metrics, connectivity-related metrics, such as network connectivity and routing-related metrics such as end-to-end delay of the routing performance can be easily measured.
- The technology of Serialisation and Deserialisation is implemented in the framework. The mobility information of every mobile node can be stored into files and re-used for further research. For example, a snapshot of the topology at a particular time can be generated in SVG by re-processing these files.

A design of network emulator for mobile ad hoc networks was proposed for the purpose of achieving a more accurate evaluation. By taking advantage of the framework for mobility-concerned simulation, the mobility and the environment information can be taken into account in the emulation of mobile ad hoc networks.

The serialisation files can be uploaded to the emulator and processed by each computer node which represents the individual mobile node, thus the mobility of mobile nodes in the environment can be aware of during the emulation. The network layers for the emulated mobile ad hoc networks and testbed are designed and described. As there might be many mobile nodes to be emulated, JBoss technology is adopted into the design to enhance the scalability of this emulator.

8.3 FUTURE WORK

The following work is included in future work of this research:

- Implement the IAMB framework into the self-positioning algorithm to increase the performance of self-positioning algorithm and the LLBR protocol. Intelligent Autonomous Mobile Bridges (IAMBs) provides a solution to increase the connectivity of mobile ad hoc networks by employing a number of extra roaming entities (IAMBs) which change their trajectories in order to maintain the connectivity of the network. The IAMBs are situated agents (i.e. operating in the same network as the mobile nodes) which roam the network trying to detect disconnected partitions. The benefit of these extra entities is that they can be thought of as a supporting set of nodes which continually monitor the network and reactively improve the connectivity. In this research, especially the Environment-Aware Mobility model and the mobility-concern simulation framework also contribute to the IAMB framework. The details can be found on the PhD thesis [100]. By using IAMB entities, the issues caused by the network partitioning in the self-positioning algorithm and the LLBR protocol are expected to be solved;
- A tool could be created to enable the environment to be created visually from the environment objects. Currently in order to construct the environment, users have to create the SVG file manually, which is not convenient when there is a very large and complex environment to be studied. Since the SVG technology has been accepted widely as an industrial standard, software like Microsoft Visio and many others support SVG file. However, these files all contain some redundant software-specific information which is not necessarily understood by our framework. A simple SVG drawing tool is definitely a should-have plug-in. Researchers could use this tool to

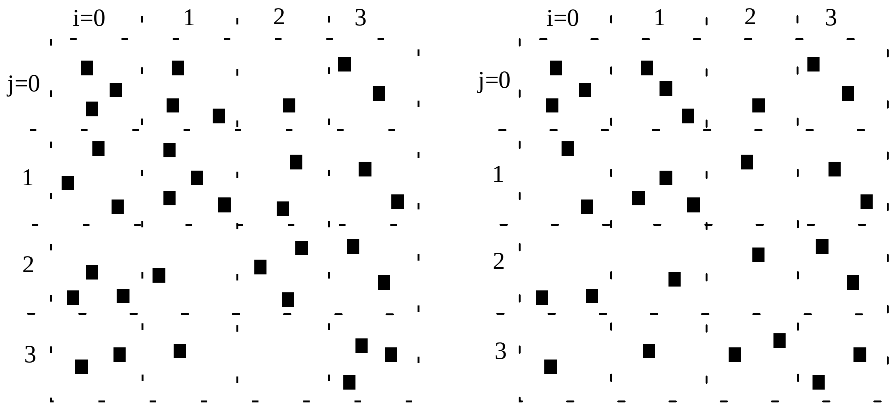
draw the environment layout and the Environment-Layout file and Environment-Configuration file can be automatically generated and be imported to the framework.

- Evaluate the performance of LLBR in all sorts of environments by using the framework developed in this thesis. Several conventional routing protocols such as AODV have been evaluated under some complex environments and the results have shown the significant impact of the environment on the performance of the routing protocol. The LLBR protocol runs OK in open space. However it needs to be tested in other environment as much as possible. The framework in this research can definitely be used.
- In this work, the impact of the mobility of mobile nodes has been thoroughly discussed and also evaluated in particular environments. In the future, this work needs to be carried on to explore a general idea how each factor of the mobility and the environment contribute to the impact. In other words, ideally the mobility can be described in more mathematical way. The proposal is followed.

If the idea of grid is used to define the distribution (probability) *D* of mobile nodes, *D* can be defined as:

$$D = \sum^{N} \frac{n_{ij}}{G} \bullet w_{i-1, j+1} \tag{8.1}$$

where, n_{ij} is the number of nodes in a grid, G is the number of grids and $w_{i+1, j-1}$ is a sort of weight factor for each grid. Here we consider $w_{i\pm1, j\pm1}$ as the summation of numbers of Mobile Nodes (MNs) in the four neighbour grids of grid (*i*,*j*). Therefore, it is possible to achieve a higher distribution of MNs in MANET with more MNs in each grid or in its neighbour grids. Figure 8.1 illustrates two example topologies. For instance in Figure 8.1(a), for the grid (1,1), $D_{1,1} = \frac{4 \times (3 + 3 + 2 + 1)}{16} = 2.25$, whereas $D_{1,1} \quad \frac{3 \times (3-2-1+1)}{16} \quad 1.3125$ in Figure 8.1(b).



(a) (b)

FIGURE 8.1 CALCULATION OF THE DISTRIBUTION OF MOBILE NODES USING GRID

Further, parameter M_E is defined by following equation to represent the environment part of mobility:

$$M_E \quad S/(D \bullet R) \tag{8.2}$$

According to the definition of M_E, the distribution of mobile nodes and transmission range of antenna have negative influence on the M_E since larger distribution index and range will cause higher density MANET and higher connectivity among the mobile nodes. Given larger *S*, the mobile nodes can have more free space to move inside the area which could cause a positive effect on M_E.

Based on our research, the key parameters associated with the mobility include entity velocity (V_e), entity direction (I_e), entity acceleration (A), entity pause duration (T_p), group velocity (V_g), group direction (I_g), number of nodes (N_e) and the number of group (N_g). To the best of our knowledge, the movement factor of mobility can be given by:

$$M_M = (A \bullet [\prod^{N_g} \int \dot{V}_g(t)] \bullet [\prod^{N_e} \int \dot{V}_e(t)]) / T_p \tag{8.3}$$

where we use vector $\dot{V}_e$ to present the speed and direction of individual MN and vector $\dot{V}_g$ to present the speed and direction of each group. If the acceleration and pause time give M_M positive and negative influence respectively, the M_M can be calculated as the average value of these two vector via the aggregations $\prod^{N_g} \dot{V}_g(t)$ and $\prod^{N_e} \dot{V}_e(t)$ ..

Thus, in conjunction with the factor of the environment, we can give the theoretical formula to describe the mobility M :

$$M \quad M_E \bullet M_M \tag{8.4}$$

This mobility formula for mobile ad hoc networks is to be evaluated and corrected.

- Complete the emulator and also implement several typical routing protocols and compare the emulation results with the simulations results. The design of the emulator has been done and the technology used for the implementation has been decided, it is believed that the mobility-concerned emulator is a valuable work and it is worthy of being implemented.

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