

The Performance of MANET Routing Protocols with Different Mobility and Propagation Models

Thesis submitted in fulfilment of the requirement for the degree of
Doctor of Philosophy
at the University of Leicester

by

Kashif Amjad
Department of Engineering
Radio Systems Laboratory
University of Leicester
October 2012.

Table of Contents

Abstract	iv
Acknowledgment	v
Chapter 1	1
Introduction	1
1.1. MANET Properties	2
1.2. Major Research Areas	5
1.2.1. Routing	5
1.2.2. Mobility	8
1.2.3. RF Propagation	9
1.3. Motivation	12
1.4. Contribution	13
Chapter 2	16
Research Method	16
2.1. Introduction	16
2.2. MANET Architecture	17
2.3. Method Of Study	18
2.4. Review of Routing Protocols	20
2.4.1. Ad-hoc On-Demand Distance Vector Routing (AODV)	21
2.4.2. Dynamic Source routing (DSR)	23
2.4.3 Optimized Link State Routing protocol (OLSR)	24
2.5. Mobility Models	25
2.5.1. Random Way Point (RWP) Model	27
2.5.2. Random Direction (RD) model	29
2.5.3. Random Walk (RW) model	30
2.5.4. Probabilistic Random (Prob-Rand) Model	32
2.5.5. Levy walk (LW) model	33
2.5.6. Reference Point Group Mobility (RPGM) model	34
2.5.7. String Model (SM)	35
2.5.8. Manhattan Grid (MG) mobility model	36
2.5.9. Gauss Markov (GM) mobility model	37
2.6. Propagation Models	38
2.6.1. Two Ray Ground (TRG) reflection model	39
2.6.3. ITU Propagation Models	41
2.6.3. ITU-LoS model in street canyons	42
2.6.4. ITU-NLoS model in street canyons	44
2.6.5. ITU-indoor Loss model	49
2.6.6. Nakagami Fading model	51
2.6.7. Lognormal shadowing model	52
2.7. Method Of Study, Assumptions and Performance Metrics	53
2.8. Literature Survey	55
Chapter 3	57
A Comparison of MANET Routing Performance using Different Realistic Propagation Models	57

3.1. Introduction	57
3.2. Network performance with slow and fast channel fading and different mobility patterns	58
3.3. Mobility scenario	60
3.4. Simulation Environment	62
3.5. Result Discussion	64
3.5.1. Packet delivery ratio	64
3.5.2. Normalized routing load	67
3.5.3. Mean end-to-end delay	68
3.6. Effects of ITU path loss models in a multi mobility environment	69
3.7. Mobility scenario	71
3.8. Simulation Environment & Results	72
3.8.1. Packet Delivery Ratio	73
3.8.2. Normalized Routing Load	74
3.8.3. Mean end-to-end delay	75
3.9. MANETS Routing Performance Analysis in a terrain aware mobility and propagation environment	76
3.10. Methodology	79
3.11. Results	80
3.11.1. Packet Delivery Ratio	80
3.11.2. Normalized Routing Load	81
3.11.3. Mean end-to-end Delay	82
3.12. Summary	83
Chapter 4	86
MANET Performances With Varying Node Mobility	86
4.1. Introduction	86
4.2. Research Background	86
4.3. Random Waypoint with attraction points	87
4.4. Mobility models scenario generation	89
4.5. Simulation Environment	90
4.6. Effect of Network Density	91
4.6.1. Packet Delivery Ratio	92
4.6.2. Normalized Routing Load	92
4.6.3. Mean End-to-End Delay	94
4.7. Network Performance with varying mobility	94
4.7.1. Packet Delivery Ratio	95
4.7.2. Normalized Routing Load	95
4.7.3. Mean End-to-End Delay	96
4.8. Impact of Leader's mobility behaviour in RPGM model on MANETS	96
4.9. Research background & methodology	98
4.10. Results Discussion	100
4.10.1. Packet Delivery Ratio	100
4.10.2. Routing Load	101
4.10.3. Mean end-to-end Delay	102

4.11. Summary	103
Chapter 5	106
Scalability in MANETS	106
5.1. Introduction	106
5.2. Simulation & Mobility Environment	108
5.3. Results & Discussion	109
5.3.1. Packet Delivery Ratio	109
5.3.2. Normalized Routing Load	110
5.3.3. Packet Collisions	113
5.4. Summary	114
Chapter 6	115
Indoor Performance of MANETS	115
6.1. Introduction	115
6.2. Simulation based AODV & OLSR Performance Comparison	115
6.3 Literature Survey	116
6.4. Simulation Environment	117
6.5. Results & Discussion	118
6.5.1. Packet Delivery Ratio	118
6.5.2 Normalized Routing Load	119
6.5.3 Mean end-to-end Delay	120
6.6. Testbed vs Simulation: An indoor MANET performance comparison	120
6.7. Literature Survey	122
6.8. Methodology	122
6.9. Results and discussion	125
6.9.1. Packet Delivery Ratio	126
6.9.2. Routing load	126
6.9.3. Round Trip Delay	127
6.10. Summary	128
Chapter 7	129
Conclusion & Future Work	129
7.1. Summary of Results	129
7.2. Directions for Future Work	132
References	134
List of Publications	144

Abstract

Simulation tools are primary means for evaluating and analysing performance of Mobile Adhoc NETWORKS (MANETS). Different mobility and propagation models have been used in this context. However, simple propagation models have been used heavily in simulation based MANETS routing performance analysis. A range of propagation models (such as ITU-R P.1411-5, ITU-R P1238-6, GOA-LoS, modified TRG, C-Shadowing and WINNER) for various indoor/outdoor and LoS/NLoS scenarios have been added into *ns-2* based simulation and results have been analysed with those readily available in the simulator for AODV, DSR and OLSR routing protocols. A variety of synthetic mobility models have been implemented under those pathloss conditions and their impact on routing performance has been observed. Heterogeneous mobility conditions have been introduced for performance analysis of AODV and DSR routing protocols under, TRG, ITU and GOA pathloss conditions.

It has been found that the DSR protocol fails to perform where AODV prevails in specific mobility environment. RPGM model have been analysed with variations of mobility model adopted by group-heads and its impact on MANETS have been investigated.

A very large adhoc network has been tested through *ns-2* simulator with comparison of ITU and TRG channel loss conditions and its results have been compared with other scalable routing performance analysis studies. Impact of corner-loss effects due to typical street movement scenario such as under MG mobility have been experimented through ITU-R based recommendations in *ns-2* simulation environment.

A small testbed based AODV performance analysis has been compared with *ns-2* based simulation results under ITU and Shadowing propagation models and significant difference have been recorded in real vs simulation based results for NRL and Mean. Delay analysis.

In summary, MANET performance have been analysed under a range of operational conditions and applications and it has been demonstrated that various factors such as mobility and propagation environment could significantly challenge the deployment of such networks.

Acknowledgment

First and foremost, all praises, thanks and acknowledgements to the Almighty Allah, who have gifted me with the priceless bounties throughout my life and have given me the physical and mental strengths that enabled me to be what I am.

Secondly, I am heartily thankful to my supervisors Dr. Alan J. Stocker and Prof. Thomas Erlebach for their fruitful discussion, exceptional support, encouragement and guidance.

Deepest gratitude is also due to my colleagues, support personnel and staff members at the University of Leicester, especially Radio Systems Laboratory research group for their beneficial and insightful comments during my talks.

I would also like to thank Bahria University, my employer, for providing me with the scholarship, support and the facilitation. Finally, I am eternally thankful to my family especially my parents and my wife, for their continual love, support and absolute confidence in me. I would also like to thank my friends in the U.K. and back home for always being there.

Abbreviations

AODV: Adhoc On-demand Distance Vector routing

AODV-UU: AODV- Uppsala University implementation

AP: Access Point

ARP: Address Resolution Protocol

BSS: Basic Service Set

CBR: Constant Bit Rate

COST-WIM: COST-231-Walfisch-Ikegami model

C-Shadowing: Combined Shadowing propagation model

CS_Threshold: Carrier Sense Threshold

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

DSSS: Direct Sequence Spread Spectrum

DSR: Dynamic Source Routing

ESS: Extended Service Set

FH: Frequency Hopping (FH)

GM: Gauss Markov mobility

GOA: Green Obaidat Adhoc propagation model

IETF: Internet Engineering Task Force

IFq: Interface Queue

ITU: International Telecommunication Union

LL: Link Layer

LW, Levy-Walk: Levy Walk mobility model

LoS: Line of Sight

MAC: Medium Access Control

MANET: Mobile Adhoc NETwork

Mean Delay: Mean end-to-end Delay

MG: Manhattan Grid mobility model

MPR: Multi Point Relays

NLoS: Non Line of Sight

ns-2: ns-allinone-2.xx

OFDM: Orthogonal Frequency Division Multiplexing (OFDM)

OLSR: Optimized Link State Routing

PDR: Packet Delivery Ratio

PHY: Physical Layer

PLCP: Physical Layer Convergence Protocol

PMD: Physical Medium Dependent

PMP: Proactive MANET Protocol (PMP)

Prob-Rand: Probabilistic Random mobility Model

RD, Rand-Dir: Random Direction mobility model

RMP: Reactive MANET Protocol

RPGM: Reference Point Group Mobility

RREP: Route REPLY

RREQ: Route REQuest

RERR: Route ERRor

RW, Rand-Walk: Random Walk mobility model

RWP: Random Way Point

RWP-ATTR: RWP with attraction points

Rx_Threshold: Receiver Threshold

Rx: Receiver

SIR: Signal to Interference Ratio

SM: String mobility Model

STD: STandard Deviation

TRG: Two Ray Ground model

Tx: Transmitter

UHF: Ultra High Frequency

VANET: Vehicular Adhoc NETwork

WINNER: Wireless world INitiative NEW Radio

WLAN: Wireless Local Area Network

Chapter 1

Introduction

Mobile wireless networks are an appealing and fast growing means to provide communication facility in many challenging environments. A mobile ad-hoc network (MANET) is a wireless network formed by the collection of mobile nodes that have the ability to form a communication network without the help of any infrastructure. MANETS have introduced a new era of networks, which can be established in an environment where the infrastructure does not exist, was destroyed by any disaster or it is not cost effective to build it.

The classification of wireless networks has been described by [Rao09] in Table 1.1.

Table 1.1:Wireless Networks classification (from [Rao09])

Network Name	IEEE Standard	Commercial Name	Geographical Size
Wireless Local Area Network (WLAN)	802.11	WiFi	Building
Wireless Personal Area Network (WPAN)	802.15	Bluetooth, ZigBee	Room
Wireless Metropolitan Area Network (WMAN)	802.16	WiMax	City
Wireless Wide Area Network (WWAN)	802.20	GSM, UMTS, MBWA	Whole earth
Wireless Regional Area Network (WRAN)	802.22	Cognitive Radio	Short Range

The Institute of Electrical and Electronics Engineers (IEEE 802.11) standard defines Medium Access Control (MAC) and Physical Layer (PHY) specifications for fixed, portable and moving stations within a local area. A moving station (also known as a node) is a device that has a IEEE 802.11-

conformant MAC and PHY layer interface to the wireless medium [IEEE07]. The IEEE 802.11 standard is further divided into two operational modes, i.e. infrastructure based and adhoc mode. Figure 1.1 shows the network formation based upon both modes. A Basic Service Set (BSS) is a group of IEEE 802.11 nodes those can communicate with each other through a specialized station known as an Access Point (AP) in a Wireless Local Area Network (WLAN). An AP can be connected to wired infrastructure through an uplink port such as Ethernet. Multiple BSS can be connected together through their up link interfaces forming Extended Service Set (ESS) network. In an Adhoc network BSS (also known as independent BSS), nodes form a network without AP and communicate via peer-to-peer.

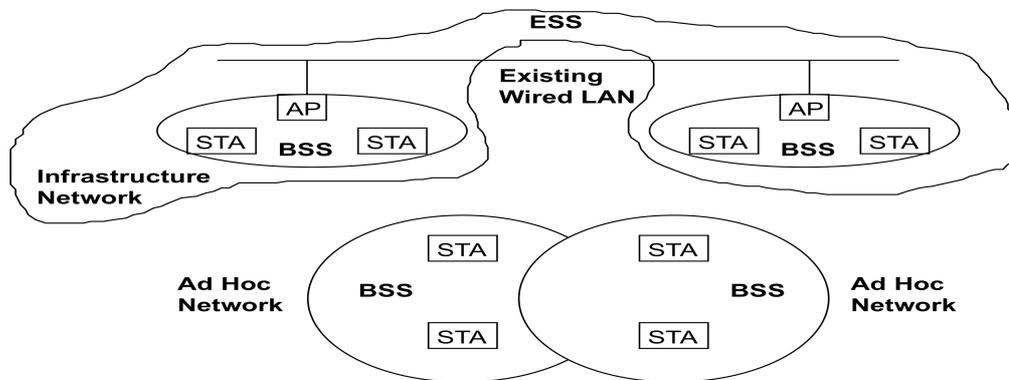


Figure1.1: IEEE 802.11 based WLANs

1.1. MANET Properties

Due to the lack of centralized infrastructure, MANETS exhibit special characteristics such as

-Decentralization: Self-configuration and decentralization are key characteristics in MANETS. The absence of a fixed infrastructure means that the communicating nodes in the network must also handle routing.

-Dynamic Topology: Nodes in MANETS are generally free to move in and around the network field. This behaviour causes frequent changes to the network topology and imposes significant constraints on network performance. In order to overcome these challenges, many routing algorithms have been proposed and discussed in the MANETS literature. Mobility induced route change and packet losses will be discussed further in Chapters 3,4, 5 and 6.

-Bandwidth Constraints: Due to the wireless nature of the network, nodes in MANETS operate in a bandwidth constrained environment resulting in a lower throughput, higher delay and response time and frequent disconnection compared to wired networks. The lower capacity of wireless links can lead to high congestion problems in MANETS.

-Energy Constraints: Nodes in MANETS are often handheld devices such as laptops, palmtops and PDAs that operate on limited battery power and may run out of power during network operation. Many energy efficient routing techniques have been proposed in the literature, which enhance the network capability such as by reducing routing paths [Jones01]. Hidden and exposed terminal problems (i.e. when two nodes start communicating with a third node simultaneously without them sensing each other as shown in figure 1.2-a or node C has to wait till node A finishes its session with node B shown in figure 1.2-b) may arise due to limited transmission range or inability of nodes (i.e. to transmit or receive) [Boukerche08], [Wu00].

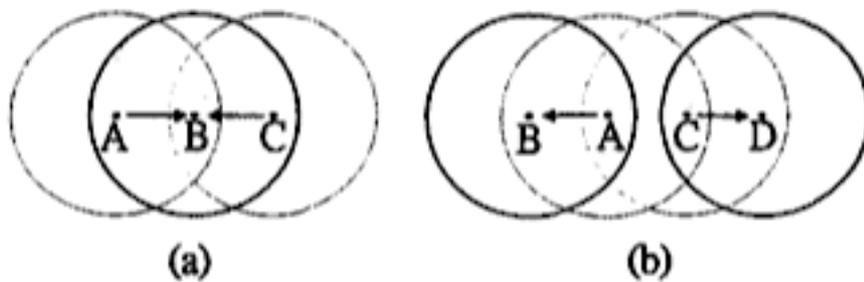


Figure 1.2: Hidden (a) & Exposed (b) Terminal issues [from Wu00]

-Asymmetric nodes: MANETS may be formed by the nodes with different transmitting powers (hence different ranges), antennas etc. Figure 1.3 shows a typical asymmetric scenario where Node 2 considers Node 1 as a neighbour whereas Node 1 cannot sense Node 2 as a neighbour as it is outside of its transmission range.

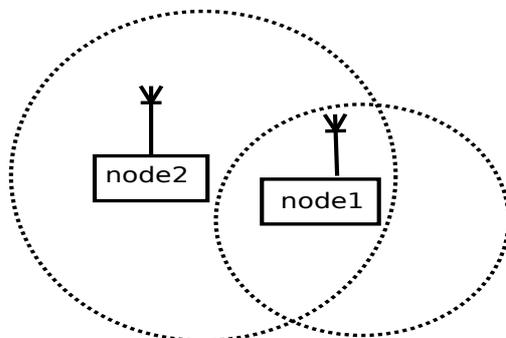


Figure 1.3: Asymmetric nodes

-Limited Neighbourhood: Nodes have limited transmission range so have limited neighbourhood in MANETS.

-Security Hazards: Due to the wireless nature of the transmission medium and the lack of centralized infrastructure, nodes are more susceptible to malicious attacks in MANETS.

1.2. Major Research Areas

Due to ease of deployment, MANETS find many applications in various fields such as military scenarios, emergency/disaster relief works, mesh networks, vehicular communications and wireless sensor networks etc. However, MANETS face many challenges posed by dynamic topology, battery constraints, network partitioning, scalability and security etc. Until today, most of the research work about MANETS has been done through simulation tools and very few testbeds based studies have been conducted mainly due to cost and scalability issues. Due to the widespread use of simulation based analysis of MANETS, the research community can only conjecture about wide spread future use of such networks with some solution to anticipated problems.

There are three major areas of study in MANETS:

- Routing
- Mobility
- Wireless Propagation

Each of these will be discussed in more details below.

1.2.1. Routing

Routing is the phenomenon of transferring information from a source node to a destination node in a network environment. In general, the routing concept in MANETS is similar to other networks i.e. firstly determining the routing path

from source to destination node and secondly transferring the data (packets) through that path. The Internet Engineering Task Force (IETF) has formed the MANET working group whose purpose is to standardise IP routing protocol functionality suitable for wireless routing applications within both static and dynamic topologies with increased dynamics due to node motion or other factors [IETF97]. In general, the IETF MANET working group has classified the routing protocols into two broad categories based upon routing strategy.

- Proactive MANET Protocol (PMP)
- Reactive MANET Protocol (RMP)

Figure 1.4 shows some of the MANET protocols classified by the IETF.

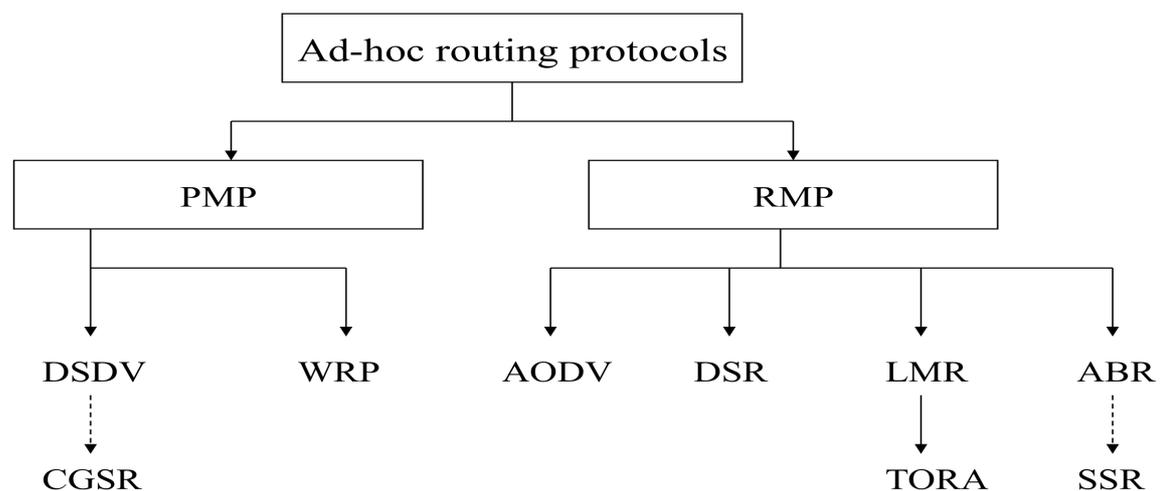


Figure 1.4: Classification of some Adhoc Routing Protocols by IETF

Proactive protocols are the ones that know the route to the destination node in a pre-determined fashion by keeping and updating routing tables. Whereas in reactive routing protocols, routes are only created when there is a need for transmission. Both of these types have their own advantages and disadvantages. e.g. the latency for route discovery is generally lower in proactive protocols because the route tables are always maintained without

any transmission need. In contrast, reactive protocols can cause higher route discovery latency because the route from node A to node B will only be maintained if node A wants to communicate with node B. On the other hand, reactive protocols have lower routing overheads because routes are only discovered if required but the proactive protocols may result in higher routing overheads due to continuous routing updates.

Depending upon network structure, MANET routing protocols have been classified as flat routing, hierarchical routing and geographic position assisted routing (see Figure 1.5 [Hong02]). In flat routing, each node participating plays an equal role in the routing process, whereas under the hierarchical routing scheme, selected nodes have more routing responsibilities than general nodes. In geographical position assisted routing, nodes must be equipped with positioning system hardware such as GPS. Chapter 2 provides more explanation of the MANETS routing protocols, which are then used in the simulation.

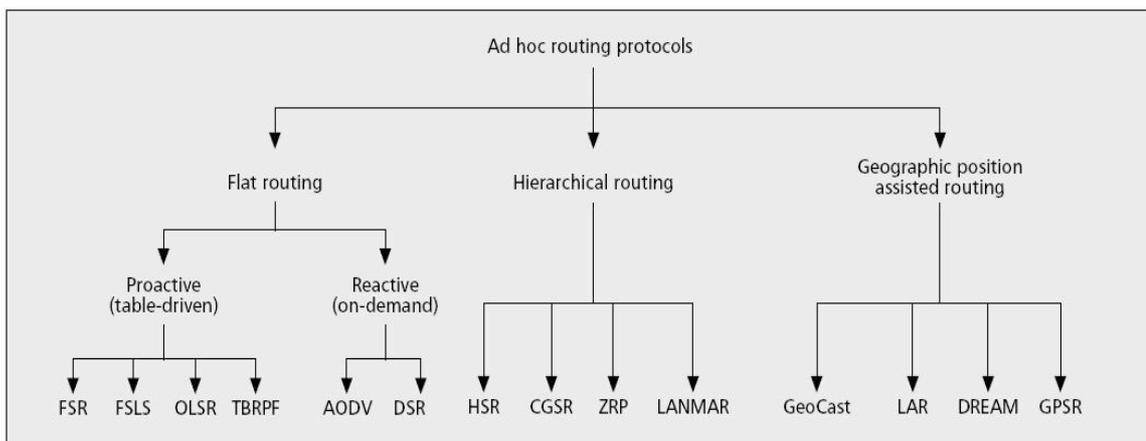


Figure 1.5: MANET Routing Classification (from [Hong02])

Routing is the most extensively studied feature of MANETS [Djenouri05]. In adhoc networks, nodes may move, causing existing links to break and the establishment of new routes, so the mobility (i.e. how nodes move) of nodes plays an important role on the performance of routing protocols. Routes between two communicating nodes may consist of hops via other nodes in the network. Therefore, finding and maintaining routes in a MANET is nontrivial.

1.2.2. Mobility

Mobility plays an important role in network stability in MANETS. Routes between communicating nodes change rapidly due to mobility. A higher mobility can cause routes to destabilise and that can result in higher packet losses. The varying mobility can affect not only the communicating nodes but also the intermediate nodes. The classification of mobility and mobility models can be done on the basis of controllability and model construction [Bai04]. Generally, mobility models used for MANET studies have been divided into synthetic and trace based mobility models. Synthetic mobility models are based on random probabilistic processes to simulate the mobility of the nodes, whereas the trace based mobility models are based on mobility patterns those are observed (i.e. such as wifi Access Point based or GPS based traces). Camp *et al* [Camp02] have divided synthetic mobility models in entity and dependent mobility models. In entity models, node movements are independent of each other whereas nodes in dependent models have temporal and spatial dependencies. Bai and Helmy [Bai04] have further divided the synthetic mobility models into four broad categories (see Figure 1.6) as random, temporal based, spatial based and with geographic

restrictions. In random mobility models, nodes move randomly and freely by choosing speed, direction and destination independent of other nodes. In temporal dependent models, a node's motion is related to its behaviour (i.e. velocity, direction) in the past. In spatial dependent models, two or more nodes can have high motion dependency (i.e. when two or more nodes are moving in the same direction to simulate group movement). Whereas in geographical restricted models, nodes are bound to follow map restrictions such as roads, lanes and pathways.

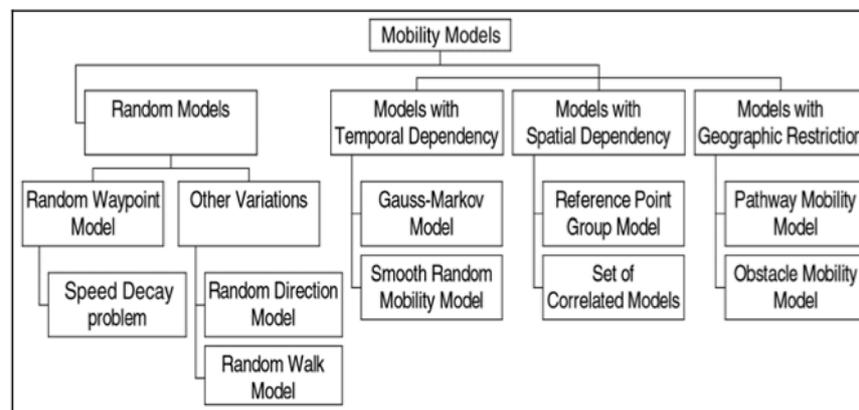


Figure 1.6: Classification of Mobility Models (from [Bai04])

There are several mobility models that have been suggested for the MANETS in the literature in the past few years. For ad-hoc networks, tracing the actual behaviour of mobile nodes is a hard process and researchers mostly use synthetic models [Bettstetter01]. A detailed description of mobility models used in the simulation work of this thesis will be discussed in Chapter 2.

1.2.3. RF Propagation

Wireless communication peers create mobile ad-hoc networks spontaneously in an infrastructure-less environment. These devices communicate directly with each other when they are in transmission range. In urban and sub-urban

scenarios, the wireless propagation is impaired by many geographical obstructions, which includes buildings, road signs, cars, indoor environment etc. The process that effects the free space propagation can be generally characterized into the following four phenomena's.

Reflection: Reflection occurs when a RF wave (such as IEEE 802.11 network compliant radio wave) impacts an object, which has larger dimensions than the wavelength (i.e. distance between the repeating units) of the propagation wave. Reflection can be caused by many objects such as building, walls, roof, furniture etc. Reflection of the main signal from various objects is referred to as multipath.

Refraction: This can be described as the bending of the radio wave due to passing through a medium of different density. For example, RF wave passing through different density of atmosphere (i.e. such as dry to wet climate) may change its direction away from the receiver.

Diffraction: This phenomenon can be described as the RF wave bending around an object such as the street corner (i.e. typical case of MANET nodes communicating in street movement scenarios).

Scattering: Scattering happens when the medium through which the RF wave travels have objects that are smaller compared to the wavelength of the signal and the number of obstacles per area (causing multiple reflections) is large.

The RF wave phenomena's can further be visualized by Figure 1.7.

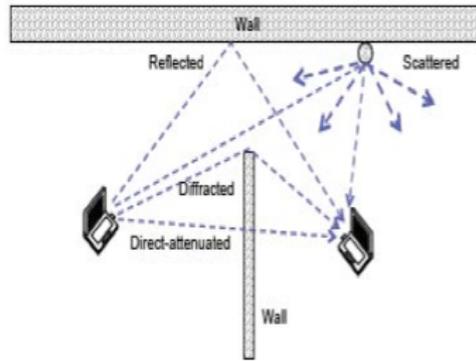


Figure 1.7: RF wave phenomena's (from [Eltahir07])

Network simulation tools are frequently used to analyse the performance of MANETS protocols and applications. These tools model the applications running on mobile devices, the wireless network protocols stack, radio signal propagation and the mobility of nodes. The radio propagation models used in common MANET simulators assume an obstacle free area and a free line of sight between the communicating nodes. As a result, a simple circle around the nodes models the communication range. However, this does not model the radio wave propagation in a typical scenario in urban and sub-urban areas. Due to the nature of self-organisation, the dynamic topology caused by mobility and transmission power control, and the multiple-hop routing in MANETS, it is difficult to build a complete analytical model to study the network performance [Eltahir07]. On the other hand, the majority of published MANET studies have used simplistic propagation models such as Free Space and Two Ray Ground model [Zang07] for simulation purposes. This results in more optimistic rather than realistic network performance analysis.

There are many empirical indoor and outdoor RF propagation models developed for wireless communications. Radio channels are much more complicated to analyze compared to wired channels. Generally, propagation

models are categorised into two cases i.e. large scale and small-scale propagation models. Large-scale models take into account the fact that the radio wave has to travel longer distance with increasing distance between mobile nodes. Small-scale models calculate the signal strength depending on small movements or small time frames. There have been several site-specific and generic propagation models developed and proposed by various research groups and telecommunication agencies for mobile wireless scenarios. The International Telecommunication Union (ITU) is the United Nations mandatory agency for information and communication technologies. The ITU Radio communication Sector (ITU-R) plays a key role in radio frequencies spectrum and satellite orbit management. Various propagation models for indoor and outdoor wireless scenarios have been recommended and kept updated by ITU-R chapter. In this thesis, ITU-R P.1411-5 [ITU-R 1411] & ITU-R P.1238-6 [ITU-R 1238] recommendations of LoS and NLoS urban outdoor and indoor propagation have been used in analysing MANET routing performance for the first time. These models have been added in the *ns-2* simulation environment and the results from there were then compared with the TRG model. These models will be described in details in Chapter 2.

1.3. Motivation

Mobility and the propagation environment are the most influenced phenomena affecting the performance of MANET routing protocols. There have been several simulation studies done about routing performance analysis of MANETS with varying mobility patterns and wireless propagation models. However, a majority of MANETS performance analysis studies have used the

simplistic wireless propagation models for routing performance investigation. This behaviour often results in over optimistic than realistic network performance. In urban areas where future MANET applications are most likely to be deployed, simplistic propagation models will not represent the wireless signal attenuation factors caused by reflection, diffraction, refraction and scattering and will result in overly optimistic network performance analysis. Furthermore, synthetic mobility patterns are commonly used in MANETS performance analysis. However, impact of heterogeneous mobility (i.e. mixed synthetic mobility) on MANETS performance along with dynamic propagation loss conditions (such as ITU outdoor LoS model) have not been analysed before in this context. Group mobility models are frequently used to mimic group motions such as in case of military platoons or emergency relief services operating in battlefield/disaster areas. However, mobility behaviour adopted by group heads in group mobility scenarios have been ignored and found to have significant impact on MANET performance analysis. Moreover in literature, scalability of MANETS have been tested for very large networks using simple physical layer environment and have not been analysed for urban mobility conditions with corner loss effects (i.e. typically experienced by antennas close to ground such as in case of MANETS). Finally, MANET testbed studies have been analysed in isolation (i.e. not comparing simulation vs. testbed environment). However, it is critically important to analyse simulation studies with testbed environment.

1.4. Contribution

Motivated by the above observations, we have implemented a range of deterministic and probabilistic propagation models (such as ITU LoS & NLoS

models [ITU-R 1238][ITU-R 144], Green & Obaidat Adhoc LoS model [Green02], Combined Log-normal Shadowing model (C-Shadowing) and Wireless world INitiative NEW Radio model (WINNER) [[Kyosti07]]) for various indoor/outdoor scenarios and also have modified the Two Ray Ground model (TRG) [Rappaport96] into network simulator 2 (*ns-2*) for an obstacle aware MANET environment.

Slow and fast fading conditions with a range of mobility models have been analysed in first part of Chapter 3. The second part of Chapter 3 investigates the MANET performance under heterogeneous mobility conditions along with a range of realistic (i.e. for adhoc networks) propagation loss models. The last part of this chapter inspects the MANETS performance in an obstacle aware mobility and propagation conditions.

Furthermore, the effect of various mobility models on network performance has been simulated. Chapter 4 investigates the performance of Adhoc On-demand Distance Vector routing (AODV) [Perkins03] and Dynamic Source Routing (DSR) [Johnson98] with variation of Random WayPoint (RWP) [Broch98] mobility and it has been found that DSR is susceptible to poor performance due to RWP mobility with increasing network density. The second part of Chapter 4 investigates the significance of leaders mobility behaviour and its crucial impact on MANET performance in a group mobility environment. The Reference Point Group Mobility (RPGM) [Hong99] model has been used as a synthetic mobility model to mimic group motion of nodes (i.e. nodes move in group formations with group leaders). However, it is critically important to consider the mobility behaviour of group leaders.

Thirdly (in Chapter 5) we have analysed the performance of a very large adhoc network (i.e. up to 1000 nodes) considering AODV protocol and using TRG and ITU-R path loss models in an urban NLoS scenario with corner loss effects typically found in urban areas.

Fourthly in Chapter 6, we have tested the performance of reactive and proactive routing protocols in an indoor simulation environment with indoor path loss models such as ITU-R P.1238-6 [ITU-R 1238] and WINNER [Kyosti07]. The second part of Chapter 6 investigates the differences between observations and simulated results for an adhoc network using AODV protocol. A small test bed with three nodes has been established and measurements have been taken for indoor scenarios and subsequent *ns-2* based simulation analysis has been done for comparison purposes.

Chapter 7 concludes this thesis by summarising all the results and possible enhancement to this work.

Chapter 2

Research Method

2.1. Introduction

This chapter introduces the background of this research while covering the literature review about MANETS routing performance analysis based upon various synthetic mobility patterns and wireless propagation models. There has been continuous research in developing new MANET routing algorithms or modifying existing routing strategies and results are often based upon considering simplistic propagation environments (i.e. not suitable for urban geographic conditions). This chapter also provides some base necessary to understand the subsequent chapters. This chapter is organised as follows. Section 2.2 covers the basic MANET architecture. Section 2.3 discusses the method of study adopted for my simulation work. Section 2.4 is about routing techniques used for the simulation work conducted during the course of my study. Section 2.5 discusses the mobility models used in the simulations and section 2.6 explains the various LoS and NLoS wireless propagation models introduced into the *ns-2* simulation environment. Section 2.7 defines the simulation environment, the performance metrics system parameters and assumptions and finally section 2.8 of this chapter covers the shortcomings of existing simulation based MANET routing performance studies in the literature.

2.2. MANET Architecture

In Chapter 1, the two working modes i.e. infrastructure based and adhoc mode of the IEEE 802.11 protocol were discussed. The IEEE 802.11 protocol covers the lower two layers of the OSI reference model (i.e. Physical and Data link layer (see Figure 2.1)) as the higher layers are independent of the network architecture [Gast02]. The data link layer is further divided into two sub layers, the Medium Access Control and Logic Link Controller [Gast02]. The physical layer is also sub divided into Physical Layer Convergence Protocol (PLCP) and the Physical Medium Dependent (PMD).

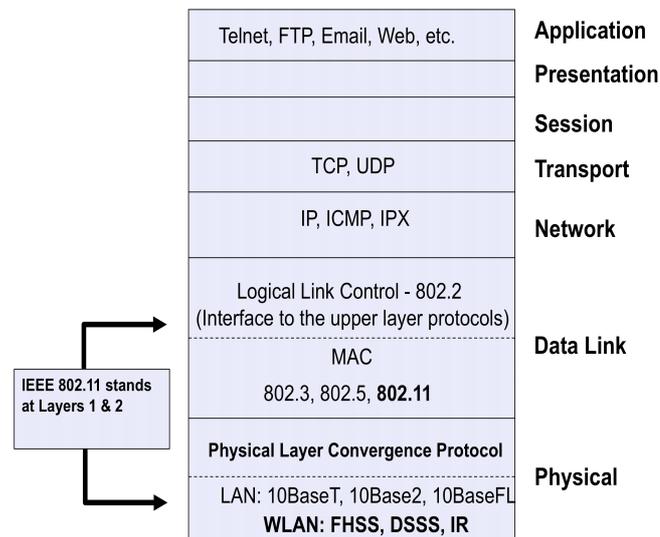


Figure 2.1: IEEE 802 reference model

The PLCP maps the MAC frames (i.e. MAC Protocol Data Units (MPDUs)) into a format, which is suitable for radio transmission. The PMD transmits the data it receives from the PLCP into the radio medium using antennas. The basic access mechanism between nodes is handled by MAC, which uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. Additionally, various physical layer standards provide different

transmission speeds and data rates using different radio frequency modulation techniques. In IEEE 802.11 ad-hoc mode, there are two main modulation or spread spectrum techniques, i.e. Direct Sequence (DS), Frequency Hopping (FH) and Orthogonal Frequency Division Multiplexing (OFDM) [Gast02].

2.3. Method Of Study

The core of this thesis (i.e. Chapters 3, 4, 5 & 6) consists of extensive simulation work conducted by using *ns-2* [ns-2-08] simulator. *ns-2* was chosen mainly because it is free and extensible. Due to the high financial cost involved in realization of a real ad-hoc network, simulation is a research tool

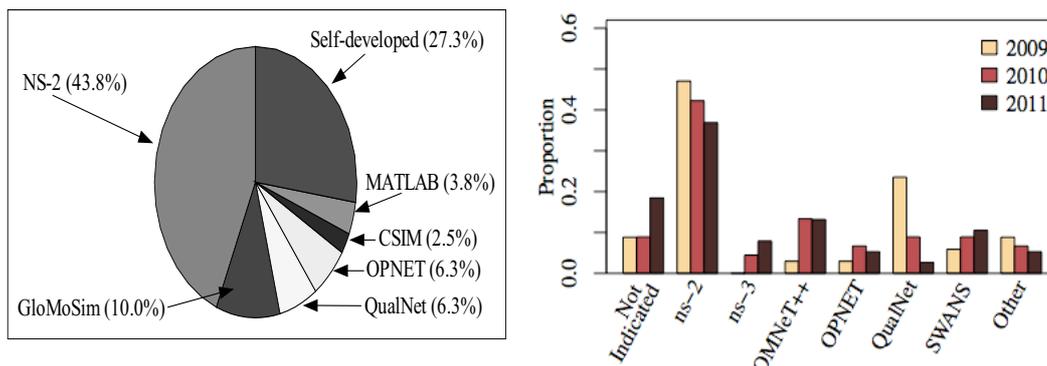


Figure 2.2: left) Comparison of usage of *ns-2* vs various other simulators [Kurkowski05] right) Distribution of network simulators used for Vehicular Adhoc networks [VANETS] simulation studies at major conferences between 2009-2011 [Joerer12]

of choice for majority of the MANET research community. *ns-2* is an open source network simulator written in a mix of C++ and OTCL. *ns-2* is the most widely used simulator (see statistics from Figure 2.2) for MANET/VANET studies [Kurkowski05] [Joerer12]. *ns-2* began as a variant of the REAL network simulator in 1989 and has evolved substantially over the past few years. The wireless model was added in *ns-2* by CMU monarch group

[CMU99] in 1999. A mobile node (see Figure 2.3) consists of various modules such as Agent, which is like an application layer from OSI model. Agent is responsible for packet generation and reception. Routing layer implements various MANET routing protocols such as AODV, DSR etc. LL (i.e. link layer) runs data link protocols and is responsible for fragmentation and reassembly of packets. It also runs Address Resolution Protocol (ARP) that resolves IP address to MAC address conversion. Interface Queue (IFQ) implements priority queue that sets higher priority for routing packets. MAC layer uses IEEE 802.11 standard. Physical Layer uses Netif (i.e. network interface module), which is like a hardware interface used by mobile node to access the channel. Radio propagation channels are implemented at this layer. *ns-2* gives a choice of four propagation models (i.e. Free Space, Two Ray Ground

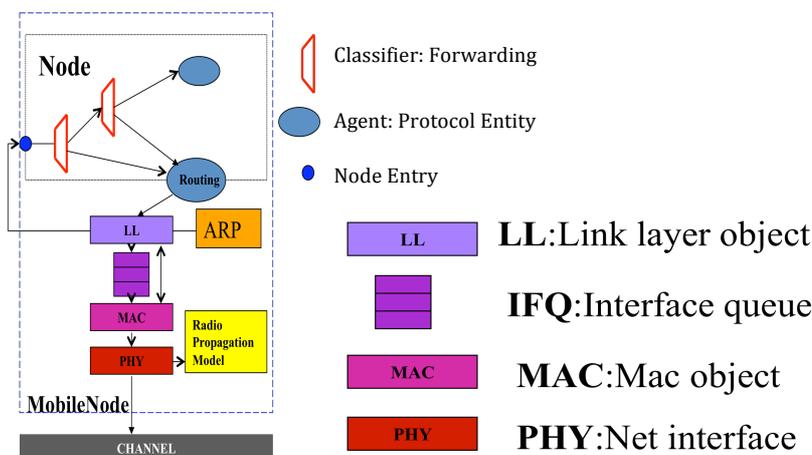


Figure 2.3: *ns-2* node module

Nakagami and Log Normal Shadowing) and by default the TRG model is used as propagation model. *ns-3* (a successor simulator of *ns-2*) [ns-3-12] has implemented some of the ITU-R models for indoor and outdoor scenarios in its current release (i.e. *ns-3.14* released on June 5, 2012 [ns-3-12]). Free

Space and TRG are the most used models for MANET protocol performance analysis and this is the focal point discussed in Chapter 3. The propagation models will be discussed in detail further in the current chapter. The simulation process in *ns-2* starts by providing the simulator with mobility traces and traffic patterns. Mobility traces describe the spatial data (i.e. nodes movement, direction, area etc) and the traffic patterns include information about the transmitting nodes, packet type, packet size and transmission rate etc. Figure 2.4 shows an example distribution of 24 nodes using *ns-2* nam

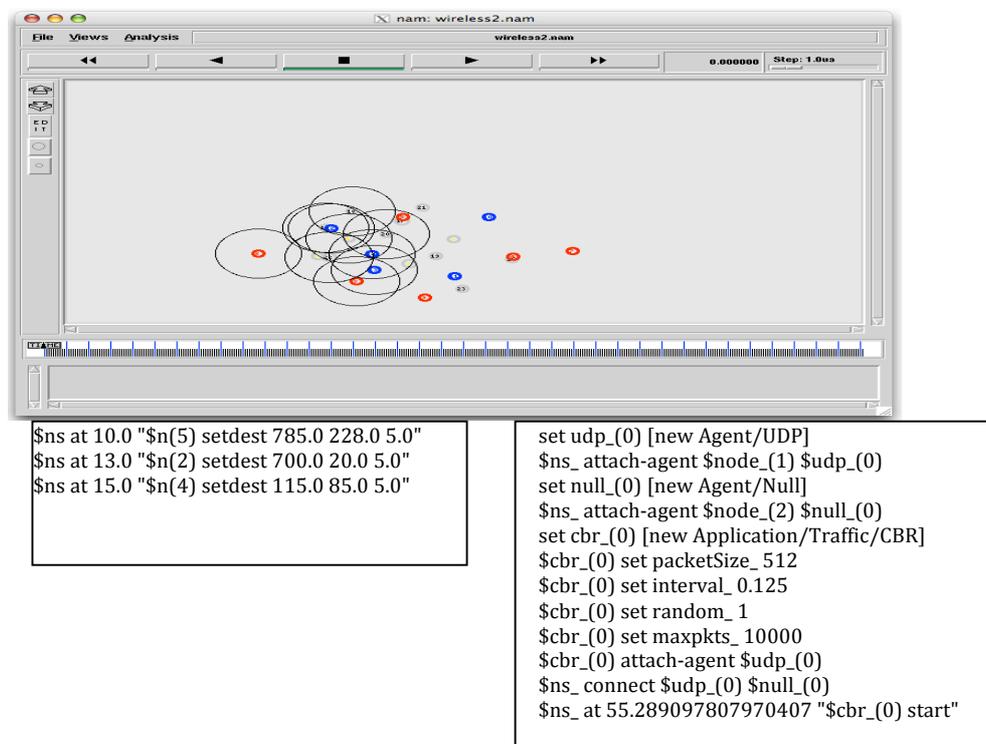


Figure 2.4: Top: Post Processing of *ns-2* trace by nam [*ns-2-08*] ,
Bottom: Example TCL script for node mobility (left) and traffic pattern (right) in *ns-2*

editor tool in *ns-2* while the node movement and traffic pattern scripts are shown on the bottom of the figure.

2.4. Review of Routing Protocols

As discussed in Chapter 1, MANET routing protocols are broadly divided into proactive and reactive categories. In MANETS, the network topology changes

arbitrarily making routing information obsolete in time and space. A routing strategy must be able to adapt to these changes. Proactive protocols are often expensive, consuming network resources (such as battery power, buffer space, channel capacity etc) but provide a quality of service routing with lower latency than with reactive protocols. This resource utilization is more significant with increasing network size and mobility in proactive protocols. These are well known issues related with the proactive approach [Perkins01]. Considering these constraints, reactive routing protocols are mainly used in this work. We have used two state of the art (i.e. AODV and DSR) reactive protocols for simulation analysis mainly because both of them are widely accepted by the research community and are also standardised by IETF MANET working group. As the core of this thesis consists of extensive simulation analysis of routing with effect of mobility and propagation environment, other routing protocols are expected to perform in a similar way. Chapter 6 covers simulation analysis of a proactive (i.e. Optimized Link State Routing (OLSR)) and reactive (i.e. AODV) protocols and the testbed performance of AODV-UU ([AODV-UU02], an implementation of AODV by Uppsala University) for indoor MANET analysis.

2.4.1. Ad-hoc On-Demand Distance Vector Routing (AODV)

This protocol was first described by [Perkins03] in 1998. Since then, this has been studied extensively and many variations have been suggested in literature [Rango11]. AODV is a destination based reactive routing protocol. When an arbitrary node 'A' wants to communicate with another node 'B' then it initiates a Route Request (RREQ) message in the network. When the RREQ message reaches the intended node, it replies with a Route Reply

(RREP) message, which travels reversely through the path along which RREQ has travelled. An intermediate node can generate a RREP message if it knows the route to the destination from a previous communication with a sequence number. The concept of sequence number is used in order to determine the freshness of route by the middle nodes. If an intermediate node is unable to forward the packet to the next hop or destination due to link failures, it generates the route error (RERR) message by tagging it with a higher destination sequence number. When the sender node receives the RERR message, it initiates a new route discovery for the destination node. An example of the AODV routing mechanism is illustrated in Figure 2.5. When a source node (i.e. N1) initiates a route discovery process (RREQ) for a destination node N8, it propagates through all available links, however RREP takes the shortest path (i.e. N8-N5-N2-N1) back to the source node. Because of reactive (i.e. On-demand) nature of AODV, this protocol can handle the dynamic behaviour of MANETS. However, MANET may experience higher latency due to reactive route discovery nature of AODV.

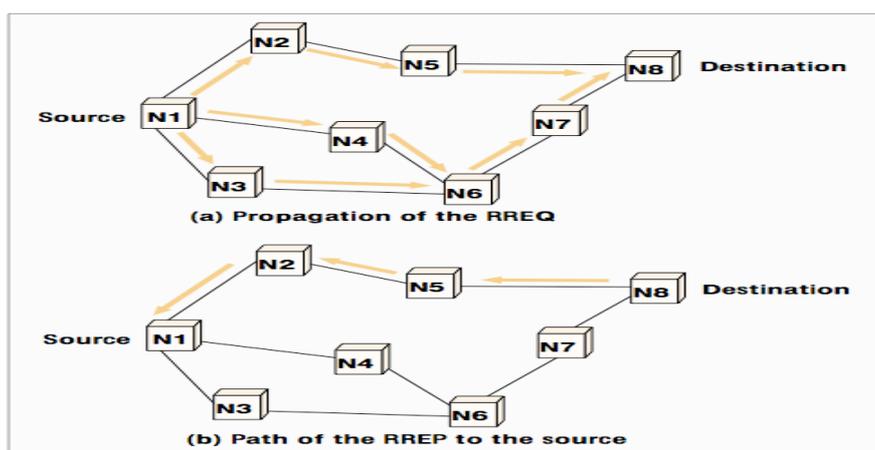


Figure 2.5: AODV route discovery process (from [Royer99])

2.4.2. Dynamic Source routing (DSR)

DSR uses source routing and caching [Johnson98] where the sender node includes the complete hop-by-hop route to the destination node in the packet header and routes are stored in a route cache. When a node wants to communicate with another node to which it does not know the route, it initiates a route discovery process with a flooding request of route request (RREQ) packets. Each node receiving the RREQ packet retransmits it unless it is the target node or it knows the route to the destination from its cache. Such a node replies to the RREQ message with a route reply (RREP) packet. The RREP packet takes the reverse path back to the source node established by the RREQ packet. This route is stored in the source node cache for future communication. If any link of this route is broken, the source node is informed by a route error (RERR) packet and this route is discarded from the cache. Intermediate nodes store the source route in their cache for possible future use. The DSR route discovery process has been shown in Figure 2.6. In comparison with the route discovery process in AODV, intermediate nodes append their route cache to the route record before propagating the RREQ. To return a RREP, the responding node must have a route to the destination. Although the key feature of DSR is the use of source routing and caching, however this limits the routing scalability (i.e. packet header size grows linearly as the network grows). Furthermore, caching is beneficial in low density networks but affects adversely on network performance in high density networks. Stale routes (i.e. faded with time and node mobility) can badly affect the network performance incurring congestion and resulting in

extremely high routing load and Mean delay in specific network environments (i.e. will be discussed further in Chapter 4).

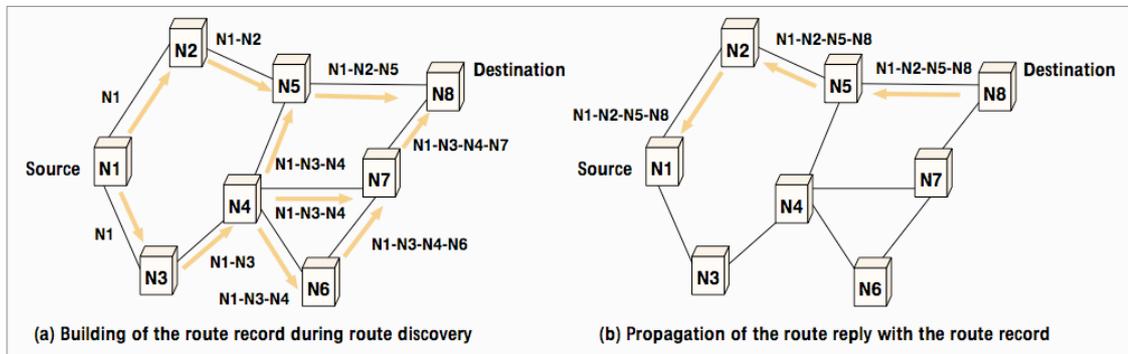


Figure 2.6: Creation of the route record in DSR (from [Royer99])

2.4.3 Optimized Link State Routing protocol (OLSR)

OLSR protocol is a table driven proactive routing strategy developed by [Thomson03]. This protocol uses the concept of Multi Point Relays (MPRs), which significantly reduce the frequency of control packets. An MPR is a node's one-hop neighbour, which is chosen to forward packets. So, the packets are forwarded by node's MPR instead of all nodes as commonly done in reactive protocols such as AODV or DSR. This technique reduces the network overheads by avoiding the flooding of routing packets. MPRs help providing the shortest path to the destination node. All MPRs periodically declare the link information (i.e. one hop neighbours) for their MPR selectors (i.e. the nodes who have selected them as MPR). The network topology information is maintained by the exchange of link state information. Reducing the maximum time interval for periodic control message transmissions can optimize the reactivity to topological changes. Figure 2.7 shows the MPR set of node A. A node such as node 'A' (from Figure 2.7) periodically broadcasts HELLO messages to its immediate (first hop) neighbours in order to exchange

neighbourhood information. From neighbourhood information, node 'A' calculates the nodes that are two hops away and computes the minimum set of one hop relay points required to reach the two hops neighbours which are MPR nodes. As from Figure 2.7, nodes 'E,F & G' are MPR nodes selected by Node 'A' covering all two hop neighbour. The idea behind using the MPRs is to choose nodes in a network covering effectively the entire network. The concept of MPRs reduces control information and broadcast traffic (i.e. saving bandwidth). However, route taken from source to destination may not be the shortest path (i.e. forwarding through MPRs) resulting in routing delays.

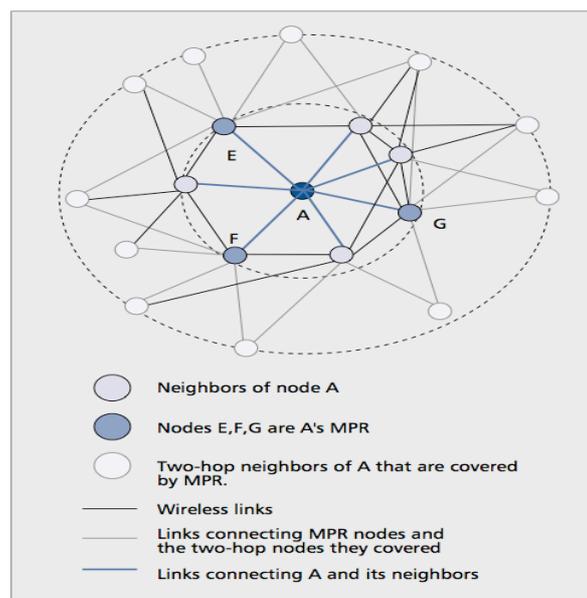


Figure 2.7: An illustration of MPRs in OLSR (from [Hong02])

2.5. Mobility Models

Mobility models should attempt to simulate the mobility behaviour of nodes in real life scenario. Synthetic mobility models are generally used for simulation analysis of MANETS mainly due to ease of use and higher scalability features

in comparison with trace based mobility patterns. In this research, synthetic mobility models are used largely due to the following reasons.

1. There are very few traces of human mobility available in the public domain. Some of the available mobility databases such as CRAWDAD [Kotz05], that are collected using Bluetooth and WiFi AP connectivity, have certain limitations. For example, the data collected in [Henderson08] was from the users in the same WiFi AP areas. So, two or more users (being in communication range of each other but using different AP) were linked to separate groups. Furthermore, the data collected represents the usage pattern while users being stationary in different AP areas. So although it is a real data, it does not completely reflect the real world mobility scenario with respect to communication range of nodes.

2. Mobile telecommunication companies record the mobility pattern of users for analysis however they do not share it publically due to data privacy and competitive advantage over other companies.

3. Most of the available real data sets have been recorded in specific scenarios such as campus or conference scenarios [Kotz05] and that makes it difficult for their generalized use.

4. Real data sets have certain limitations that cannot be altered such as node speed, node density and scalability, which are key elements in the analysis of routing algorithms performance.

In this research, synthetic mobility patterns covering all categories defined by Bai and Helmy in [Bai04] (i.e. random, temporal, spatial and geographic conditions) are used. There have been various other synthetic mobility models

(apart from the ones mentioned below) described in literature. However we have chosen the ones those are significantly used in literature ([Roy11], [Jayakumar08], [Natarajan10], [Spyropoulos06]). The following section explains the mobility models that are used in subsequent chapters.

2.5.1. Random Way Point (RWP) Model

The Random Way Point (RWP) mobility model is the simplest and most widely available model for MANETS studies [Broch98]. The algorithm for RWP is as follows.

1. A node chooses a random destination anywhere in the network area.
2. The node starts moving towards the destination with a velocity randomly chosen from a speed vector $[0, V_{max}]$.
3. After reaching the destination, the node stops at the destination for a duration specified by the 'pause time' parameter, which is the same for all nodes. The nodes then repeat from stage 1.
4. All nodes repeat this procedure until the simulation ends.

Figure 2.8 shows the distribution and mobility trace of 20 nodes for 250 secs of an example run of the RWP mobility model. In RWP mobility pattern, nodes tend to take longer straight trips passing through or near the centre of the network field (see Figure 2.8-b). This behaviour of nodes causes clustering in the middle of the simulation field more significantly with long simulation runs. This non-uniformity of nodes has significant impact on routing performance results and has been reported in literature [Bettstetter02] with some variations

such as attraction point (i.e. hotspots visited by nodes more frequently) in the simulation area.

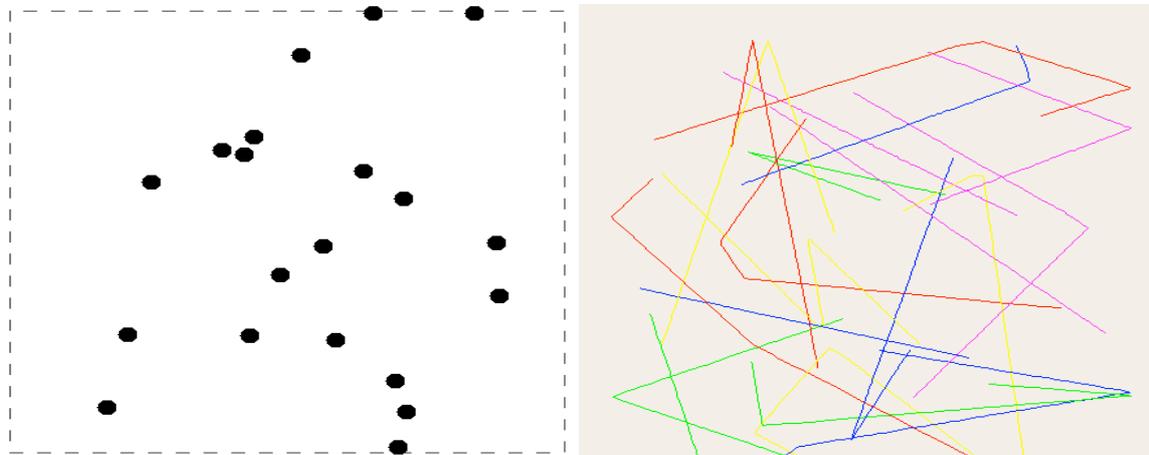


Figure 2.8: Plots of (left) 20 nodes randomly distributed by RWP model and (right) footprints of nodes
Maximum velocity: 2 m s^{-1} , grid size $500\times 500\text{m}$, simulation time 250 sec, zero pause time (continuous motion)

Figure 2.9 shows the dwell time analysis of nodes with simple RWP and with hotspots (i.e. attraction points such as labs, café in a campus scenario) in a rectangular network field. It is evident that, without attraction points, nodes stay longer in centre of the simulation area than around the borders.

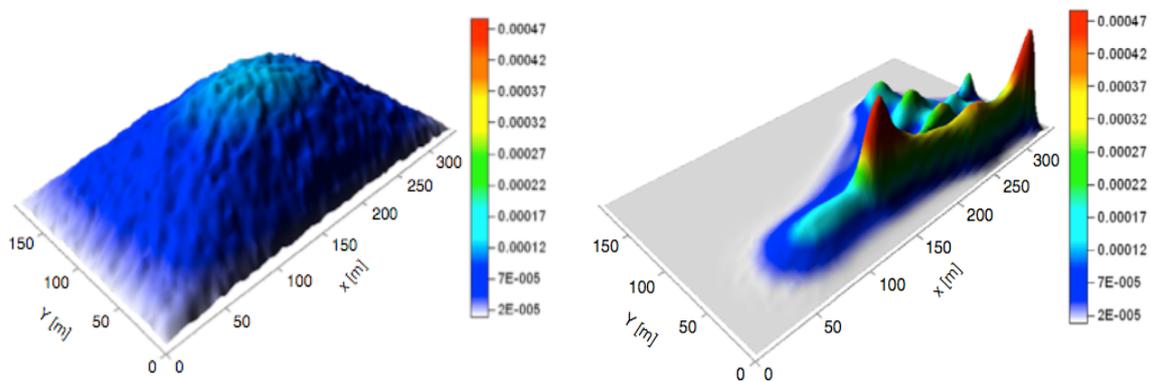


Figure 2.9: Distribution of nodes- histogram over simulation area visualizing the dwell time for RWP (left) and RWP with attraction points (right) (from [Aschenbruck07]).

2.5.2. Random Direction (RD) model

This model is capable of overcoming the non-uniform spatial distribution problems typically found in Random Waypoint mobility model. In this model, a node randomly chooses a direction to move along until it reaches the boundary of the simulation field. The velocity and direction of the mobile node does not change until it hits the boundary. After reaching the boundary, it stops for a specified pause time and then it chooses another angular direction (between 0 and 180 degrees) to travel. In this way, the typical problem (i.e. higher node density in the middle of simulation area) found with Random Way Point mobility model has been resolved. Figure 2.10 shows the distribution of mobility trace of 20 nodes for 250 secs and with zero pause time (i.e. continuous motion) of an example run of the RD mobility model.

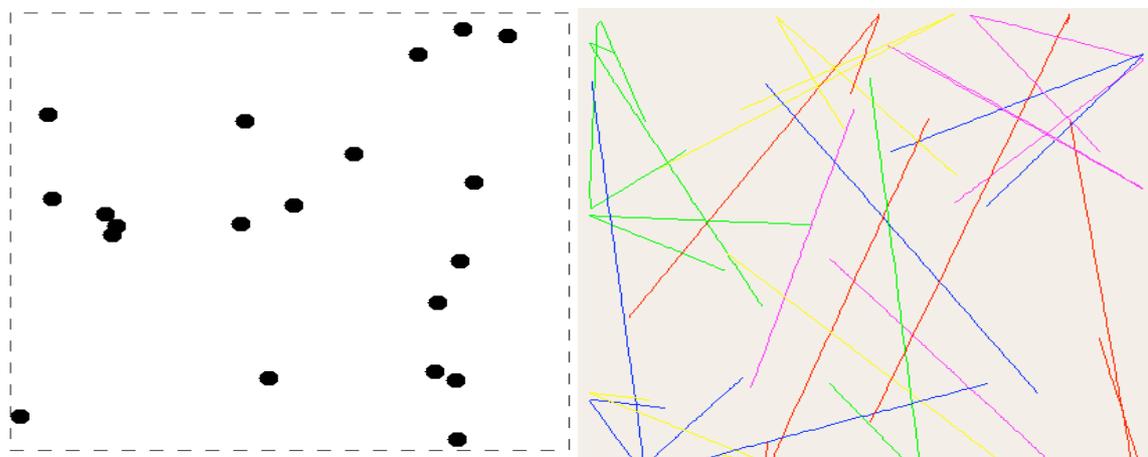


Figure 2.10: Plots of (left) 20 nodes randomly distributed by RD model and (right) footprints of nodes
Maximum velocity: 2 m s^{-1} , grid size: $500 \times 500\text{m}$, simulation time: 250 sec, zero pause time (continuous motion)

There are more chances of network partitioning and higher hop count due to longer trips taken by nodes (i.e. up to the edges of the simulation field), [Camp02] following RD mobility model and may incur higher network delays (such as processing and propagation). In comparison to the node distribution

in RWP model (Figure 2.8), RD mobility model shows more distributed movement of nodes in the simulation field.

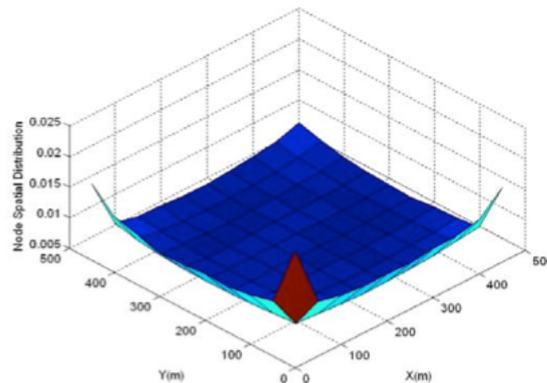


Figure 2.11: Spatial Node Distribution of RD mobility model (from [Mousavi07]), Maximum velocity: 20m s^{-1} , grid size: $500 \times 500\text{m}$, simulation time: 1000 sec, pause time: 10 s

2.5.3. Random Walk (RW) model

The random walk mobility model was first introduced in [Guerian87] for wireless network simulations. This model is a discrete version of Brownian motion originally proposed to emulate the unpredictable movement of particles in physics first quantified by Einstein [Einstein06]. Under this model, some nodes will move in an unexpected way. Random Walk model was proposed to mimic the unexpected movement patterns of nodes [Camp02]. This is a memoryless mobility model that is a node's current state does not depend on its past behaviour (i.e. magnitude of velocity and direction), which results in sudden changes in the movement direction. At each time interval, a nodes speed and direction is changed. Spatial node distribution for 20 nodes simulation (following RW mobility algorithm) is shown in Figure 2.12. It is clear that nodes distribution is more dispersed in RW model than with RWP and RD models. (i.e. higher in centre area with RWP and on edges area with RD model).

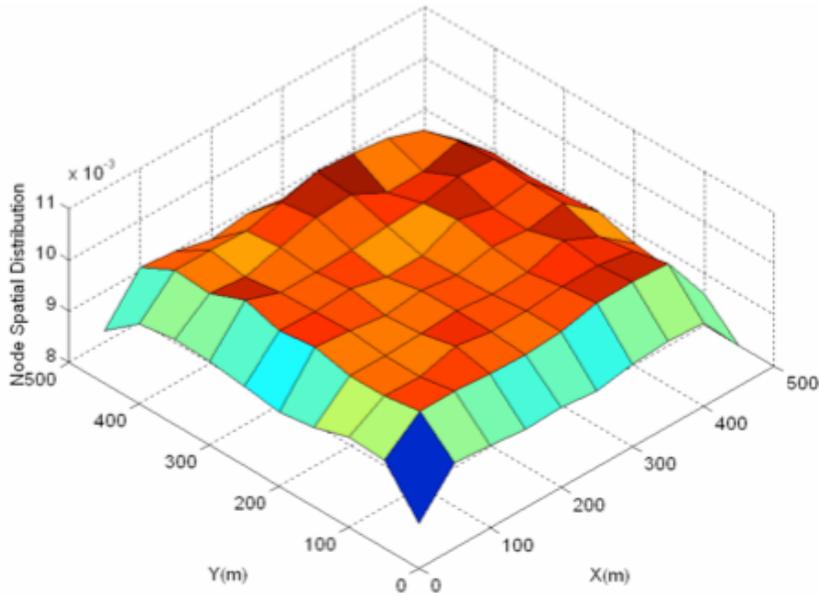


Figure 2.12: Spatial node distribution in RW mobility model (from [Mousavi07]), Maximum velocity: 20 m s^{-1} , grid size: $500 \times 500\text{ m}$, simulation time :1000 sec, pause time: 10 s.

Figure 2.13 shows the screen shot and mobility trace for 250 secs with 20 nodes following RW mobility pattern. It can be stated that nodes show unexpected mobility behaviour (i.e. frequent turnings) while following RW mobility algorithm.

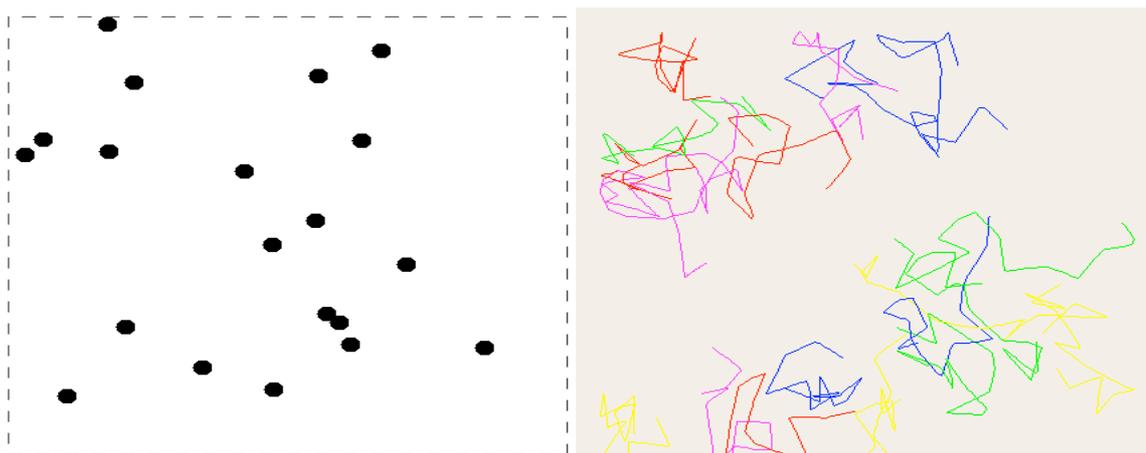


Figure 2.13: Plots of (left) 20 nodes randomly distributed by RW model and (right) footprints of nodes Maximum velocity: 2 m s^{-1} , grid size $500 \times 500\text{ m}$, simulation time 250 sec, zero pause time (continuous motion)

2.5.4. Probabilistic Random (Prob-Rand) Model

This model utilizes a probability matrix to determine the position of a particular mobile node in the next time step which has three different states (0,1 and 2) for its x and y position [Chiang98]. The probability matrix used is

$$P = \begin{bmatrix} P(0,0) & P(0,1) & P(0,2) \\ P(1,0) & P(1,1) & P(1,2) \\ P(2,0) & P(2,1) & P(2,2) \end{bmatrix}$$

Where each entry $P(a,b)$ explain the probability of a mobile node going from state a to state b. The probability matrix allows a mobile node to move in any direction as long as it does not return to its previous position. State '0' represents the current position (x or y) of a mobile node, state '1' represents the previous position (x or y) and state 2 represents the mobile nodes next position (x or y) if the mobile node continues to move in the same direction. This implementation produces probabilistic motion rather than pure random motion, which may represent a more realistic behaviour [Chiang98]. Figure 2.14 shows the screen shot and mobility trace for 250 secs with 20 nodes following Prob-Rand mobility pattern. In Prob-Rand model, nodes tend to take shorter trips and move in localized areas comparing with RWP, RD and RW models. The probability matrix used for these traces was same as used originally by Chiang [Chiang98].

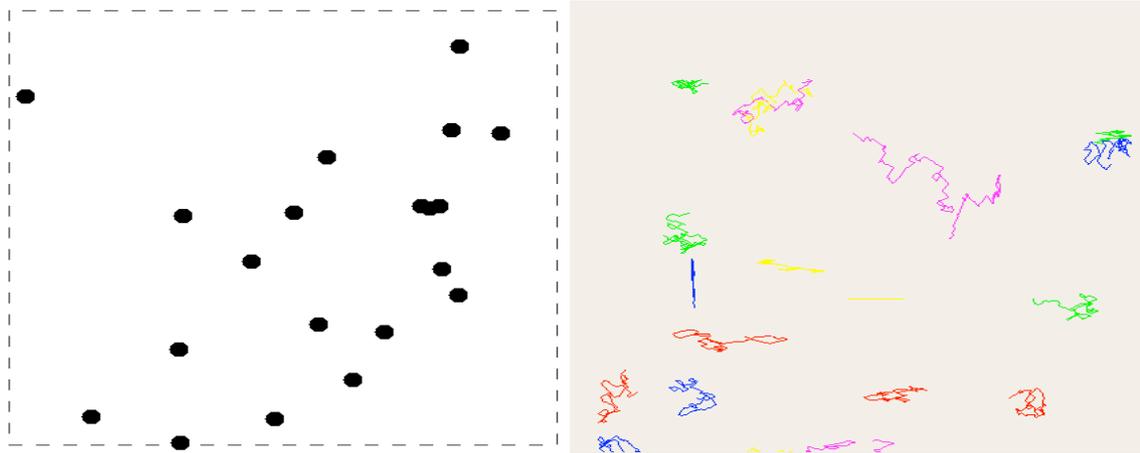


Figure 2.14: Plots of (left) 20 nodes randomly distributed by Prob-Rand model and (right) footprints of nodes. Maximum velocity: 2m s^{-1} , grid size $500 \times 500\text{m}$, simulation time 250 sec, zero pause time (continuous motion)

2.5.5. Levy walk (LW) model

A Levy walk is a random walk in which the walk times (flight times) have a power-law distribution (i.e. walk and pause times distribution closely follow power law) [Shlesinger93]. In this model, each motion has four attributes, i.e. l , θ , Δ_{tf} , Δ_{tp} . Each node takes a random direction θ and a flight length l . A flight is a straight motion by node without changing speed and direction. Δ_{tf} indicates the flight duration or flight time, which is chosen for each flight from a probability distribution $p(l)$. Using the values of Δ_{tf} and l , the model calculates the speed of flight. Δ_{tp} indicates the pause time duration taken by nodes after each movement. In [Broch98], the authors have analyzed human travelling patterns in the scale of several hundred to thousand kilometres and shown that human long distance travelling patterns show Levy walk patterns. In [Shlesinger93], the authors have mentioned that human travelling patterns are not of random Levy walk type because it does not make sense that humans move in a pure random fashion. By studying several real world mobility traces, Rhee *et al* [Rhee07] have concluded that human mobility

patterns are not purely random based and outdoor movements are like Levy walk mobility patterns. From literature survey, it can be considered that this model is more realistic than other random models for human travelling patterns. Figure 2.15 shows the screen shot and mobility trace for 250 secs with 20 nodes following LW mobility pattern. It is visually evident that nodes move completely in different manner with LW patterns than with other random models.

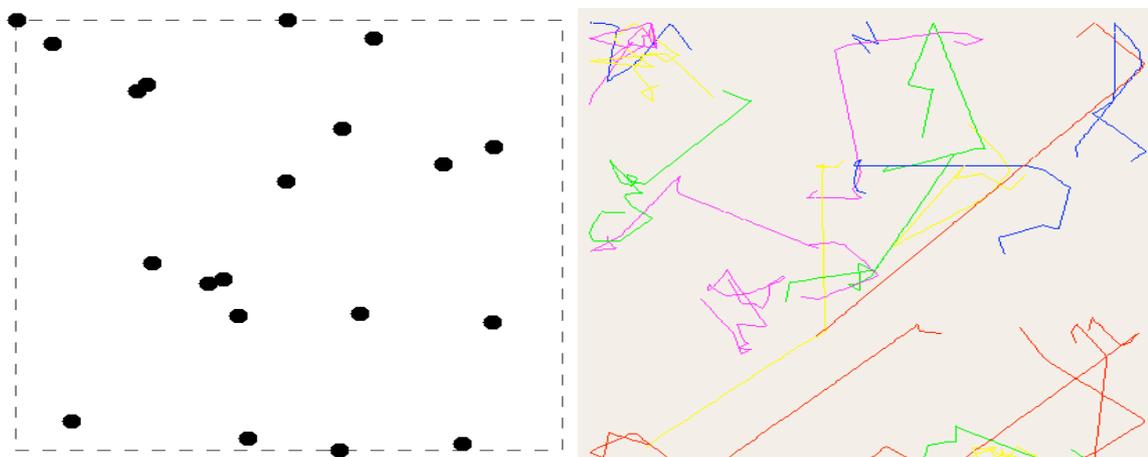


Figure 2.15: Plots of (left) 20 nodes randomly distributed by LW model and (right) footprints of nodes
Maximum velocity: 2m s^{-1} , grid size $500\times 500\text{m}$, simulation time 250 sec, zero pause time (continuous motion)

2.5.6. Reference Point Group Mobility (RPGM) model

In this model, which was first described by [Hong98], nodes are divided into groups each with a group leader. In the standard RPGM model, the leader's mobility is based on the Random Waypoint model and the group members follow the movement of the respective group leaders closely. So, there is a virtual centre to each group and the nodes move randomly around the virtual centre. The movements in groups can be characterized as follows.

$$|\vec{V}_{member}(t)| = |\vec{V}_{leader}(t)| + random() \times SDR \times max_speed \dots (2.1)$$

$$\theta_{member}(t) = \theta_{leader}(t) + random() \times ADR \times max_angle \dots (2.2)$$

The Speed Deviation Ratio (SDR) and Angle Deviation Ratio (ADR) parameters are used to control the deviation of the velocity (magnitude and direction) of group members from that of the leader. Since follower nodes chase their cluster heads within each group, the mobility pattern adopted by head nodes strongly influences the overall mobility behaviour observed in this model.

Figure 2.16 shows the screen shot and mobility trace for 250 secs with 20 nodes (divided equally in four groups) following RPGM mobility pattern.

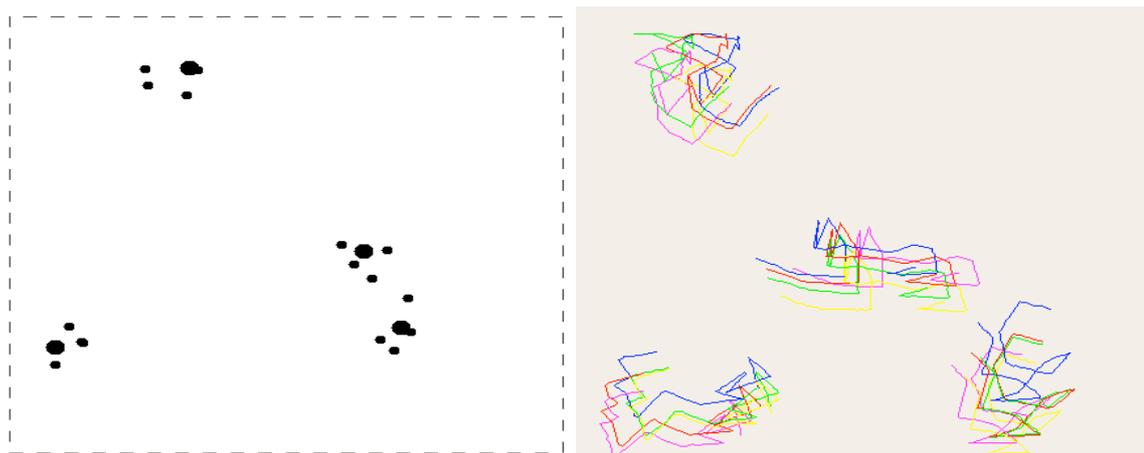


Figure 2.16: Plots of (left) 20 nodes randomly distributed by RPGM model and (right) footprints of nodes
Maximum velocity: 2 m s^{-1} , grid size: $500 \times 500\text{ m}$, simulation time: 250 sec, zero pause time (continuous motion)

2.5.7. String Model (SM)

This is a variation of RPGM model. In this model, nodes move in groups as well but follow their respective group leaders in a row rather than being randomly around group leader as in case of RPGM model and can be more realistic group movement in some specific scenarios. Figure 2.17 shows the screen shot and mobility trace for 250 secs with 20 nodes following SM

mobility pattern. In comparison with RPGM mobility model, it is clear that nodes move in lanes behind respective leaders in SM model.

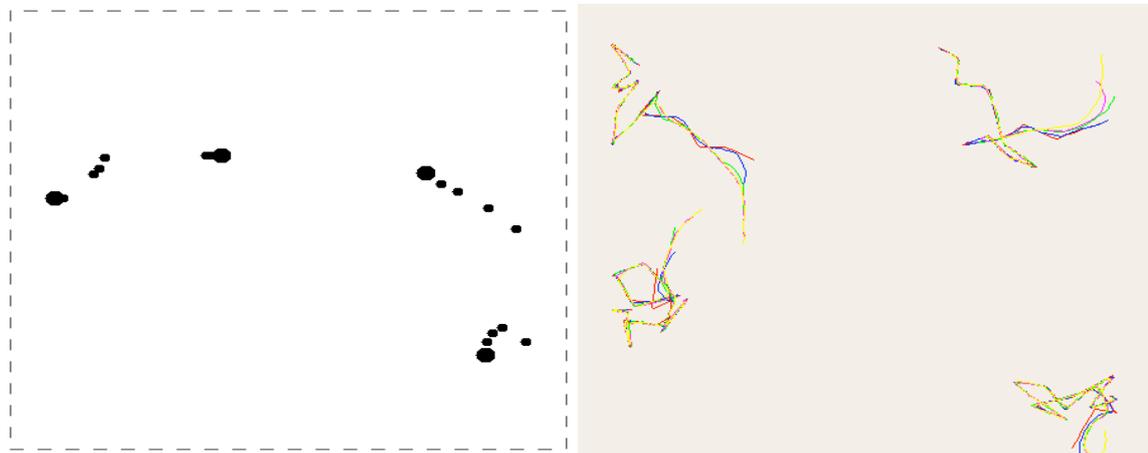


Figure 2.17: Plots of (left) 20 nodes randomly distributed by SM model and (right) footprints of nodes
Maximum velocity: 2m s^{-1} , grid size: $500 \times 500\text{m}$, simulation time: 250 sec, zero pause time (continuous motion)

2.5.8. Manhattan Grid (MG) mobility model

In this model [ETSI98], nodes move in predefined pathways, e.g. nodes move in horizontal rows and vertical columns, while at the intersections nodes can turn either left or right or can carry on straight ahead. The probability of going straight is 0.5 and the probabilities of turning left or right are each 0.25. The speed of a mobile node at a given time slot is dependent on its speed at the previous time slot. A node's velocity is restricted by the velocity of the node preceding it on the same lane. So, this model imposes high spatial and temporal dependencies on nodes. This model is used in urban area scenario study as the columns and rows can simulate the effects of roads and pathways. Figure 2.18 shows a snapshot and mobility trace for 250 secs with 20 nodes following MG mobility pattern. As nodes move in restricted lanes,

resulting in scattered movements, there is more possibility of link breakages in MG mobility model.

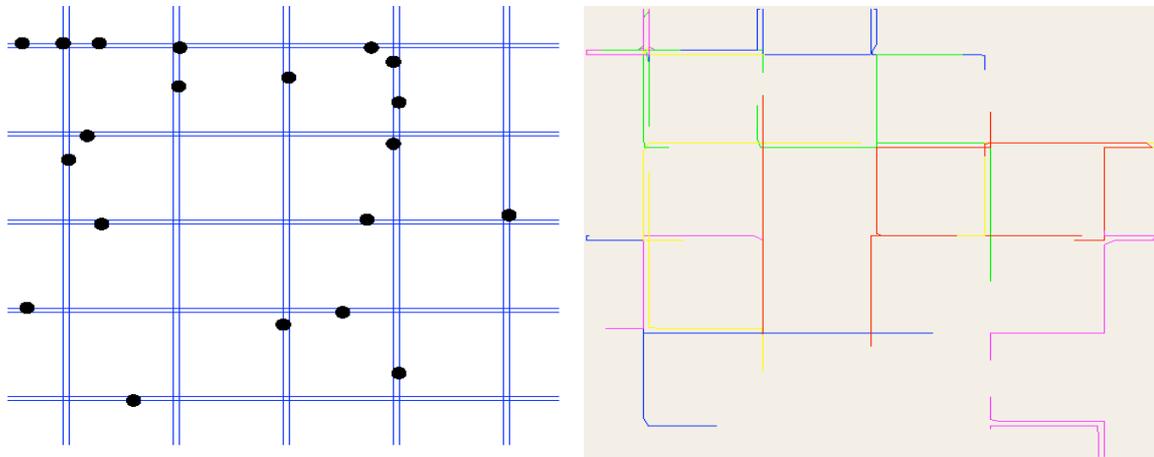


Figure 2.18: Plots of (left) 20 nodes randomly distributed by MG model and (right) footprints of nodes. Maximum velocity: 2 m s^{-1} , grid size: $500 \times 500\text{ m}$, simulation time: 250 sec, zero pause time (continuous motion)

2.5.9. Gauss Markov (GM) mobility model

The Gauss-Markov Mobility Model was designed to adapt to different levels of randomness via one tuning point [Liang99]. In this mobility model, each node is assigned with an initial speed and direction. At a fixed time interval length n , the speed and direction of each node is updated. The value of speed and direction at the n^{th} interval is calculated based upon the value of speed and direction at the $(n-1)^{\text{th}}$ interval and a random variable using the following equations.

$$\begin{aligned}
 s_n &= \alpha s_{n-1} + (1 - \alpha) \bar{s} + \sqrt{(1 - \alpha)^2} s_{\chi_{n-1}} \\
 d_n &= \alpha d_{n-1} + (1 - \alpha) \bar{d} + \sqrt{(1 - \alpha)^2} d_{\chi_{n-1}} \dots\dots\dots(2.3)
 \end{aligned}$$

Where S_n and d_n are the new speed and direction of mobile node at time interval n , α is the tuning parameter for randomness and \bar{s} & \bar{d} are the mean value of speed and direction as $n \rightarrow \infty$. $s_{\chi_{n-1}}$ and $d_{\chi_{n-1}}$ represent random variables

from Gaussian distribution for speed and direction respectively. This model is a temporal dependent model where the degree of dependency is determined by the value of α . Totally random motion is obtained by setting $\alpha=0$ and linear motion is obtained by setting $\alpha=1$ [Liang99]. Different levels of randomness can be achieved by setting values of α between 0 and 1. Figure 2.19 shows the screen shot and mobility trace for 250 secs with 20 nodes following GM mobility pattern.

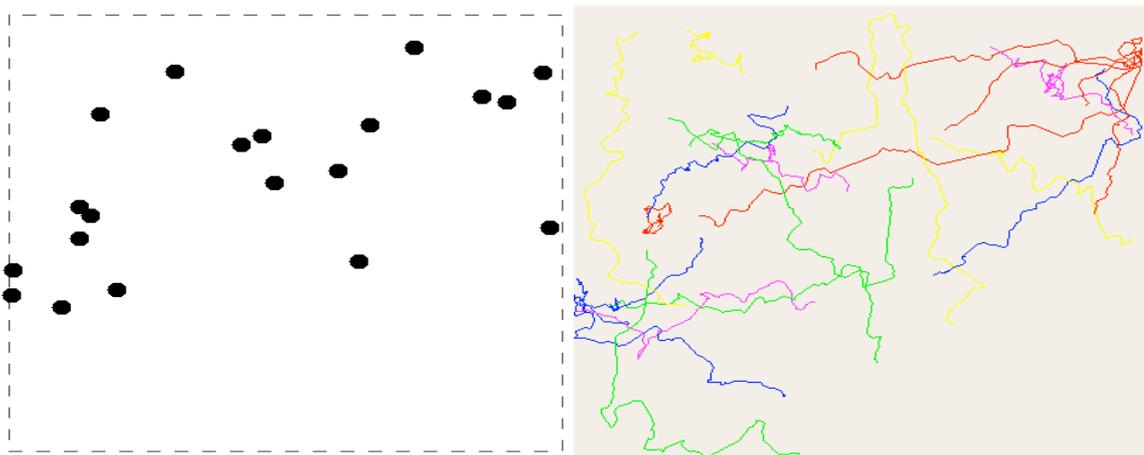


Figure 2.19: Plots of (left) 20 nodes randomly distributed by GM model and (right) footprints of nodes
Maximum velocity: 2m s^{-1} , grid size: $500\times 500\text{m}$, simulation time: 250 sec, zero pause time (continuous motion)

2.6. Propagation Models

Radio propagation considerably influences the performance of wireless communication networks. Radio propagation loss models are used in simulations to estimate the received signal strength of each packet received by a node. *ns-2* uses the threshold values (i.e. Carrier Sense (CS) and Receiver (RX) threshold), which define the minimum possible value of the received signal strength indicator by which a node is still able to communicate successfully. If the value is smaller than the threshold, *ns-2* considers that the

receiving node did not receive the packet successfully. If the received power level is less than $RX_Threshold$, the packet is received with error and if the packet is received with the power level less than $CS_Threshold$, the packet is discarded as noise and the channel is regarded as idle. The following section presents the probabilistic and deterministic propagation models used in simulation scenarios.

2.6.1. Two Ray Ground (TRG) reflection model

This model takes into consideration both direct and indirect paths between the transmitting and receiving node [Rappaport96]. This is an analytical model, which uses the following equation to calculate the approximately received power in watts.

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \dots\dots 2.4$$

Where P_t is transmitted signal power, G_t and G_r are the transmitter and receiver antenna gains respectively, d is the distance between two communicating nodes, h_t and h_r are the transmitter and receiver antenna heights and L ($L \geq 1$) is the system loss due to various sources. For $L=1$, equation 2.4 can be expressed in dB as,

$$P_r dBm = P_t dBm + 10 \log_{10}(G_t G_r) + 20 \log_{10}(h_t h_r) - 40 \log_{10}(d) \dots\dots (2.5)$$

The two-ray model does not give good results for shorter distances due to oscillation caused by the constructive and destructive combination of the two rays. Free space path loss model based upon Friis equation [Friis46] is a better choice for smaller distances. *ns-2* simulator uses a cross over distance d_c when this model is used. If $d \leq d_c$, path loss is calculated with Friis

equation and if $d > d_c$, TRG model is used .At the cross over distance, both equations produce the same results, so d_c can be calculated as

$$d_c = \frac{(4\pi h_t h_r)}{\lambda} \dots(2.6)$$

Where λ is the wavelength (m). This model has been found reasonably accurate for predicting the large scale signal strength over distances of several kilometres for mobile radio systems that use tall towers (i.e. height which exceed 50 m), as well as for LoS microcell channels in urban environments [Feuerstein94]. However, this is not a typical case in MANET scenarios. This model is readily available in *ns-2* and was implemented by the Monarch group.

2.6.2 Green & Obaidat Adhoc LoS Model

Green Obaidat Adhoc LoS model was first described in 2002 and considers the path loss due to Fresnel zone with near earth antenna height (i.e. typically between 1 and 2 meters) more accurately [Green02]. The proposed path loss for near ground antennas is as follows

$$P_{loss} = 40 \log_{10} d + 20 \log_{10} f - 20 \log_{10} h_t h_r \dots\dots(2.7)$$

Where d represents the distance between communicating terminals, f is the frequency in MHz and h_t and h_r are the transmitter and receiver antenna heights respectively. For 2412 MHz frequency band, this model can be further simplified as

$$P_{loss} = 7.6 + 40 \log_{10} d - 20 \log_{10} h_t h_r \dots\dots(2.8)$$

According to Green & Obaidat [Green02], this model proves to be more accurate than Lee [Lee86], Hata [Hata97] and COST-231 [Cichon99] for

predicting free space path loss in IEEE 802.11 WLAN LoS case with antenna heights between 1 to 2.5 meters. This model was developed using signal strength from WLAN traces in a university environment. Considering these parameters of this model, it was selected for ns-2 based MANET simulations.

2.6.3. ITU Propagation Models

This study covers the use of ITU-R P.1238-6 [ITU-R 1238] & ITU-R P.1411-5 [ITU-R 1411] for indoor and outdoor LoS-NLoS scenarios in ns-2 MANETS simulation environment. Through experimental work, these models were actually proposed for infrastructure based (i.e. such as Base Stations) short-range radio communication systems for urban/suburban scenarios. Through literature survey, it has been known that there is not any propagation model proposed yet that has been derived purely through MANETS scenario experiments. This is mainly because there is not any known reported testbed study done with the scope of modelling propagation environment for MANETS. Harrold *et al* [Harrold01] have investigated the additional attenuation to the propagation loss effects in the cases where the antenna is very near to the ground and close to the objects such as human body. Green and Obaidat [Green02] have suggested a propagation model for Adhoc networks LoS conditions based upon signal strength measurements using WLAN traces in university campus scenario. Petwari *et al* [Petwari99] have presented a pathloss model for peer-to-peer communication systems based upon measurements with an antenna height of 1.7m and operating frequency of 1.8 GHz in rural and urban areas. This model considers the pathloss with respect to distance and does not accommodate corner-loss effects typically

found in urban NLOS cases. Harrold & Nix [Harrold00] have shown that forming a mobile-to-mobile connection (using relaying) can be useful to achieve significant benefits such as reduction in transmitted power and increase in network capacity. Wang *et al* [Wang08] state that pathloss increases with lower terminal height as does the probability of LoS. It is important to consider suitable pathloss model when simulating peer-to-peer communication such as in MANETS. However, a generic, standalone propagation model addressing general MANET characteristics (i.e. infrastructure independent, low antenna heights, multi-hopping, mobility etc) is still a challenge for MANET research community. The following section provides the detailed information about the selected ITU propagation models used for MANET performance analysis in sub-sequent chapters.

2.6.3. ITU-LoS model in street canyons

This path loss model is recommended by ITU [ITU-R 1411] for typical urban areas. This model describes the path loss situation in street canyons where a line of sight (LoS) exists between transmitter and receiver. As like TRG model, ITU-R LoS recommendations have been developed for an infrastructure based environment (such as base stations) that is generally not a case in MANET scenarios. This model describes the path loss measurements in three limits (i.e. lower, median and upper bound). In the UHF frequency range, the basic transmission loss can be characterized by two slopes and a single breakpoint [ITU-R 1411]. An approximate lower bound is given by

$$L_{LoS,l} = L_{bp} + \begin{cases} 20 \log_{10} \left(\frac{d}{R_{bp}} \right) & \text{for } d \leq R_{bp} \\ 40 \log_{10} \left(\frac{d}{R_{bp}} \right) & \text{for } d > R_{bp} \end{cases} \dots\dots(2.9)$$

Where d is the communication distance, R_{bp} is the breakpoint distance and is given by

$$R_{bp} \approx \frac{4 h_b h_m}{\lambda} \dots\dots(2.10)$$

λ is the wavelength (m), h_b and h_m are the base and mobile station antenna heights respectively. The median loss value is given by

$$L_{LoS,m} = L_{bp} + 6 + \begin{cases} 20 \log_{10} \left(\frac{d}{R_{bp}} \right) & \text{for } d \leq R_{bp} \\ 40 \log_{10} \left(\frac{d}{R_{bp}} \right) & \text{for } d > R_{bp} \end{cases} \dots\dots(2.11)$$

And the approximation upper bound loss is given by

$$L_{LoS,u} = L_{bp} + 20 + \begin{cases} 25 \log_{10} \left(\frac{d}{R_{bp}} \right) & \text{for } d \leq R_{bp} \\ 40 \log_{10} \left(\frac{d}{R_{bp}} \right) & \text{for } d > R_{bp} \end{cases} \dots\dots(2.12)$$

L_{bp} is the value for the basic transmission loss at the break point, defined as

$$L_{bp} = \left| 20 \log_{10} \left(\frac{\lambda^2}{8\pi h_b h_m} \right) \right| \dots\dots(2.13)$$

This model incorporates fading margins (i.e. such as the upper bound has the fading margin of 20 dB, see Equations 2.9 & 2.12) due to multipath (i.e. reflection, diffraction and scattering) typically found in urban street canyons

environment. For $ns-2$ implementation, upper loss bound (i.e. Equation 2.12) was used.

2.6.4. ITU-NLoS model in street canyons

ITU-R describes the following two different scenarios [ITU-R 1411] for NLoS conditions in UHF frequency range.

1. Propagation over roof-tops for urban area

This recommendation describes the NLoS scenario between mobile terminal and a fixed base station where a base station is located either above or just below the rooftop height (i.e. base station height between 4 to 50 meters) in street canyons as shown in Figure 2.20. The propagation model described in this scenario is a modification of COST-231 Walfisch-Ikegami model [Cichon99] as there are few parameters changed in ITU model. This model requires the average building height, separation distance among buildings and street width information.

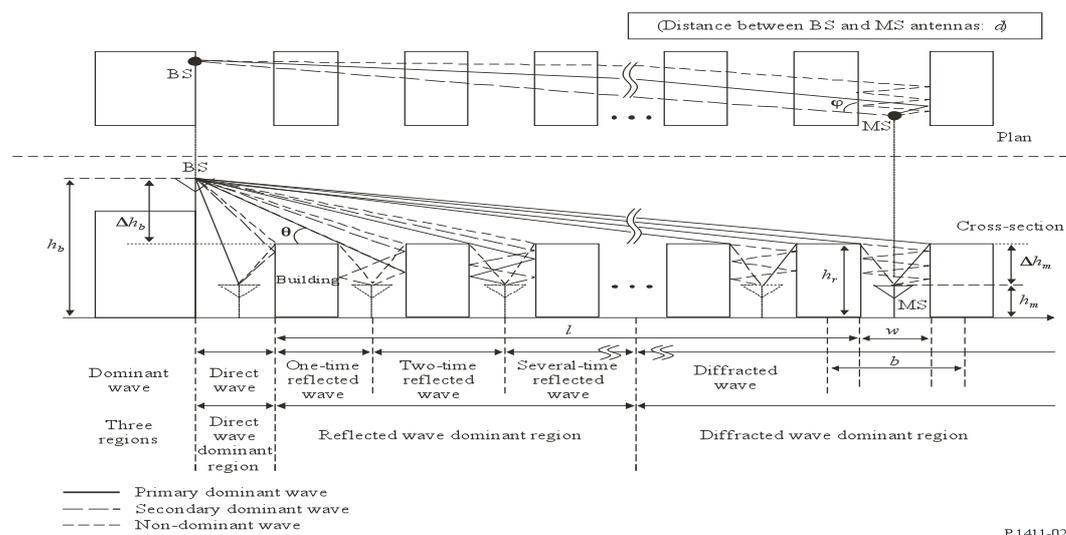


Figure 2.20: NLoS case1 between BS-MS (from [ITU-R 1411])

2. Propagation between terminals located below rooftop height at UHF

This model was originally developed by an Ofcom project [Ofcom07] based upon measurements taken in two cities (i.e. London and Reading) in U.K. The model was developed with considering the desirable features (i.e. considering some disadvantages of existing COST-231 and ITU models for example the symmetry between mobile node and BS) such as communication between mobile-to-mobile and low antenna height terminals. The model was called “Low Height Model” with the aim of developing a model for propagation between low-height terminals (see Figure 2.21) where both terminals are located within clutter (primarily, but not exclusively, urban and suburban clutter) [Ofcom07].

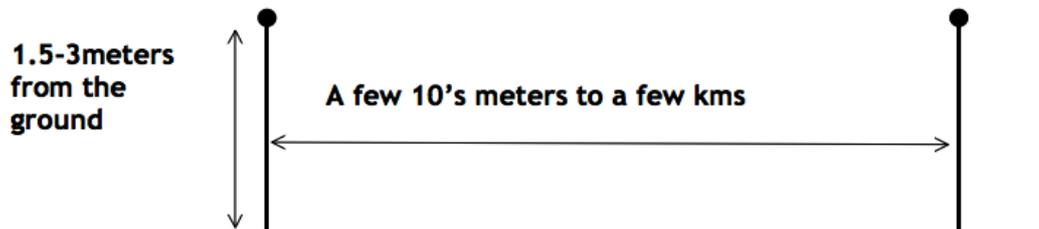


Figure 2.21: Illustration of the required ranges for height and distance between the terminals (from [Ofcom07]).

Although the multihop communication scenarios were not implemented during the development of this propagation model, this model seems to be the most suitable model for MANETS where nominal antenna height of transmitter and receiver is in between 1 to 1.5 meters (i.e. similar to human height). The original model has been determined from measurements made in the UHF band with antenna heights between 1.5 & 3.0 meters above ground. However this model is still most appropriate model to be considered for MANETS. By

comparing both ITU-models for NLoS situation, this model was selected for *ns-2* simulation environment.

This is a statistical model that calculates the path loss in LoS and NLoS regions and models the sharp decrease in signal strength in transition distance (i.e. going from the LoS to the NLoS region) known as the corner loss (see Figure 2.22).

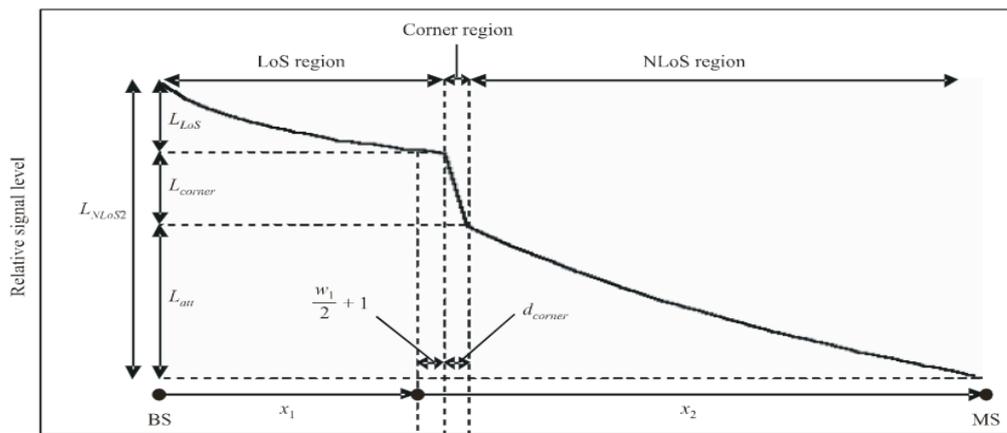


Figure 2.22: Typical trend of propagation along street canyons with low base station height for frequency range from 2 to 16 GHz (from [ITU-R 1411]).

A typical NLoS corner loss scenario between two mobile nodes is shown in Figure 2.23.

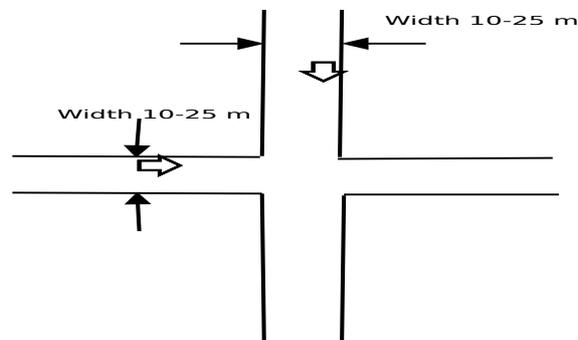


Figure 2.23: A typical urban NLoS corner loss region between two mobile nodes

Based upon the original experimental data, this model includes the statistics of location variability in the LoS and NLoS regions and provides a statistical model for the corner distance between LoS and NLoS regions [ITU-R 1411].

Firstly, the LoS (median) loss is calculated between T_x and R_x .

$$L_{LoS}^{median}(d) = 32.45 + 20 \log_{10} f + 20 \log_{10}(d/1000) \dots (2.14)$$

Where d (m) is the distance between T_x and R_x and f (MHz) is the operating frequency. For the required location percentage, p (%), this model calculates the LoS location correction factor by using the following Rayleigh cumulative distribution function.

$$\Delta L_{LoS}(p) = 1.5624\sigma \left(\sqrt{-2 \ln(1 - p/100)} - 1.1774 \right) \dots (2.15)$$

Where σ is the standard deviation (sd) recommended as 7dB through measurements.

Now the total loss is calculated as

$$L_{LoS}(d, p) = L_{LoS}^{median}(d) + \Delta L_{LoS}(p) \dots (2.16)$$

The NLoS loss is calculated as

$$L_{NLoS}^{median}(d) = 9.5 + 45 \log_{10} f + 40 \log_{10}(d/1000) + L_{urban} \dots (2.17)$$

L_{urban} depends upon the urban category and is 0 dB for suburban, 6.8 dB for urban and 23 dB for dense urban region.

The required location percentage for NLoS location correction is calculated as

$$\Delta L_{NLoS}(p) = \sigma N^{-1}(p/100) \dots (2.18)$$

Where σ is recommended as 7dB and $N^{-1}(\cdot)$ is the inverse normal cumulative distribution function.

The total NLoS loss can be calculated as

$$L_{NLoS}(d,p) = L_{NLoS}^{median}(d) + \Delta L_{NLoS}(p) \dots (2.19)$$

For the required location percentage, ($p\%$), the distance d_{LoS} for which the LoS fraction F_{LoS} equals p is calculated as

$$d_{LoS}(p) = \begin{cases} 212[\log_{10}(p/100)]^2 - 64 \log_{10}(p/100) & \text{if } p < 45 \dots (2.20) \\ 79.2 - 70(p/100) & \text{otherwise} \end{cases}$$

Values of LoS and NLoS location correction and d_{LoS} for $p=1,10,50,90$ and 99 (%) are suggested in the Table 2.1 [ITU-R 1411]. As the model was statistically developed through experimental data from two cities in U.K., it was observed that the 99 percent of time two nodes having LoS distance of 10 meters. As the LoS distance increases, its percentage decreases (see Figure 2.24).

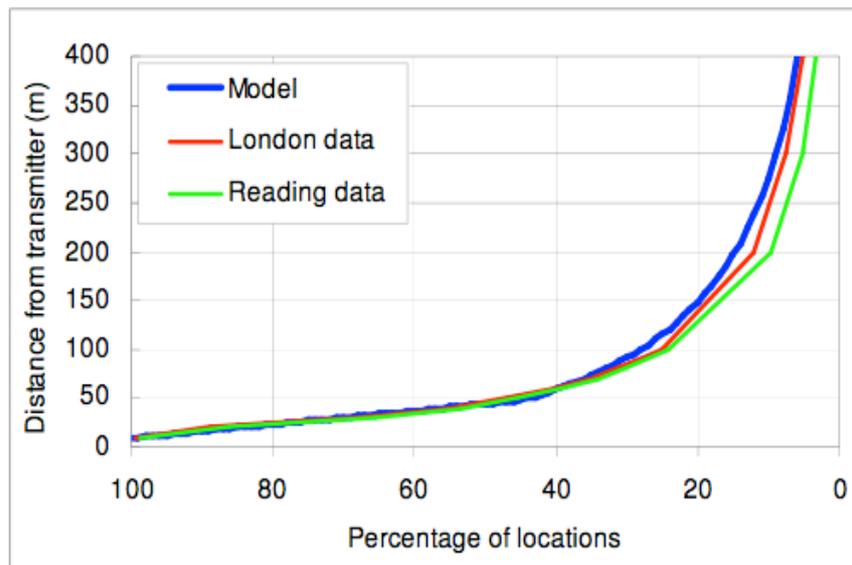


Figure 2.24: Comparison of the model (Equation 2.18) to building database in two cities (from [Ofcom07])

Table of LoS and NLoS location variability corrections

p (%)	ΔL_{LoS} (dB)	ΔL_{NLoS} (dB)	d_{LoS} (m)
1	-11.3	-16.3	976
10	-7.9	-9.0	276
50	0.0	0.0	44
90	10.6	9.0	16
99	20.3	16.3	10

Table 2.1: Table for LoS and NLoS location variability correction [ITU-R 1411].

This model suggests that if the mobile node's distance from the corner is known then $d_{LoS(p)}$ is set to that distance.

Finally the path loss at distance d is calculated by the following three conditions.

- a) if $d < d_{LoS}$, then $L(d,p) = L_{LoS}(d,p)$
- b) if $d > d_{LoS} + w$, then $L(d,p) = L_{NLoS}(d,p)$
- c) Otherwise the loss is linearly interpolated between the following values



.....(2.21)

Where width w is the street width that introduces a transition region between LoS and NLoS conditions and is typically recommended as $w=20m$ [ITU-R 1411., 2009].

2.6.5. ITU-indoor Loss model

This is a site general model as it requires little path or site information [ITU-R 1238]. The path loss can be described by the following equation

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_f(n) - 28 \dots(2.22)$$

Where f is frequency (in MHz), N is the distance power loss coefficient, d is the separation distance between T_x and R_x , L_f is the floor penetration loss and n is the number of floors between communicating nodes. Derived through various measurement campaigns, Table 2.2 shows the recommended values of distance power loss coefficients [ITU-R 1238]. Paths with a LoS component are dominated with a free space loss and have a distance power loss coefficient of around 20. For indoor NLoS scenario (i.e room to room propagation), the value of N exceeds up to 40 for a typical indoor environment (i.e. such as in office buildings) [ITU-R 1238].

Table 2.2: Power loss coefficient N for indoor transmission loss calculation [ITU-R 1238]

Frequency	Residential	Office	Commercial
900 MHz	–	33	20
1.2-1.3 GHz	–	32	22
1.8-2 GHz	28	30	22
2.4 GHz	28	30	–
3.5 GHz	–	27	–
4 GHz	–	28	22
5.2 GHz	30 (apartment) 28 (house)	31	–
5.8 GHz	–	24	–
60 GHz	–	22	17
70 GHz	–	22	–

– ‘No Data’

Table 2.3 provides the values of floor penetration loss factor L_f (dB) for various frequency and environment ranges [ITU-R 1238].

Table 2.3: Floor penetration loss factors, L_f (dB) with n being the number of floors penetrated, for indoor transmission loss calculation ($n \geq 1$) [ITU-R 1238]

Frequency	Residential	Office	Commercial
900 MHz	–	9 (1 floor) 19 (2 floors) 24 (3 floors)	–
1.8-2 GHz	4 n	15 + 4 (n – 1)	6 + 3 (n – 1)
2.4 GHz	10 ⁽¹⁾ (apartment) 5 (house)	14	–
3.5 GHz	–	18 (1 floor) 26 (2 floors)	–
5.2 GHz	13 ⁽¹⁾ (apartment) 7 ⁽²⁾ (house)	16 (1 floor)	–
5.8 GHz	–	22 (1 floor) 28 (2 floors)	–

⁽¹⁾ Per concrete wall.

⁽²⁾ Wood & mortar.

– ‘No Data’

2.6.6. Nakagami Fading model

The Nakagami distribution [Nakagami60] is a mathematical model of a wireless channel with fading. The Nakagami model is a probabilistic and generic propagation model that was first implemented by Taliwal *et al* [Taliwal04] in *ns-2* for vehicular adhoc network simulations. Nakagami distribution can be specified by the following probability density function

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp\left[-\frac{mx^2}{\Omega}\right] \dots (2.23)$$

with conditions for $x \geq 0$, $\Omega > 0$, $m \geq \frac{1}{2}$.

The pdf of power (square of the signal amplitude) at the given distance can be obtained by a change of variables and is given by a gamma distribution $\Gamma_{(m)}$ of the following form [Chen07].

$$p(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} \exp\left[-\frac{mx}{\Omega}\right] \dots (2.24)$$

Ω is the expected value of the distribution and can be interpreted as the average received power. m is called the shape or fading parameter. The values of m and Ω parameters are a function of distance. Depending on the values of m and Ω , the Nakagami distribution can be configured to model a variety of radio channels ranging from a perfect free space channel to a moderate fading channel typically found on highways.

2.6.7. Lognormal shadowing model

The simplistic radio propagation models like Free- Space and TRG model predict the received power as a function of distance d . In real world, the received power at a certain distance can vary with time due to changing multipath propagation effects. The Lognormal shadowing model implies that the measured signal level at a specific transmitter-receiver separation would have a Gaussian (normal) distribution where the measured signal level has values in dB units [Rappaport96]. The shadowing model consists of two parts, the first part predicts the mean received power as free space or two ray ground at a distance d , and is denoted by $\overline{P_r(d)}$, it uses a reference distance d_0 , $\overline{P_r(d)}$ is computed relatively to $P_r(d_0)$ by the following equation.

$$\frac{P_r(d_0)}{P_r(d)} = \left(\frac{d}{d_0}\right)^\beta \dots (2.25)$$

Where β is called the path loss exponent and is measured experimentally by field measurement. Some typical values of β are shown in Table 2.4.

Table 2.4: Path loss exponent β values [Rappaport96]

Environment		β
Outdoor	Free space	2
	Shadow urban area	2.7 to 5
In building	Line-of-sight	1.6 to 1.8
	Obstructed	4 to 6

Equation 2.25 can be further derived as

$$\left[\frac{P_r(d)}{P_r(d_0)} \right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) \dots (2.26)$$

The second part of the shadowing model reflects the variation of received power due to multipath effects. The overall shadowing model is represented by the following equation.

$$\left[\frac{P_r(d)}{P_r(d_0)} \right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB} \dots (2.27)$$

X_{dB} is Gaussian random variable with standard deviation σ_{dB} (or shadowing deviation). Equation 2.22 is also known as Lognormal Shadowing model. Some typical values for shadowing deviation (depending upon the geographical environment) are shown in Table 2.5.

Table 2.5: Typical value for shadowing deviation [Rappaport96]

ENVIRONMENT	σ_{dB}
Outdoor	4 to 12
Office, hard partition	7
Office, soft partition	9.6
Factory, line-of-sight	3 to 6
Factory, obstructed	6.8

2.7. Method Of Study, Assumptions and Performance Metrics

Chapters 3, 4, 5 and 6 mainly consist of simulation work done by using *ns-2* simulator. Since the scope of this study is to analyze the routing performance

of large networks (up to thousand nodes) for various mobility models and urban propagation environments, the use of simulation is a cost effective and achievable way to investigate these effects. However, simulation results must be validated with real test beds in order to improve the quality of work. Chapter 6 represents the comparison of a MANET testbed performance with relative simulation work for a small network.

The following general assumptions were made while conducting simulation work and have been widely adopted in the literature [Das00] [Boukerche04].

- All nodes are equipped with IEEE 802.11b compliant transceivers with the same computational and hardware resources (i.e. fully symmetric environment) and the nodes neither run out of power nor malfunction during entire simulation time.

- The number of nodes remain same in a given network topology, i.e. nodes neither leave nor new nodes join the network during given simulation time. However, network partitioning may occur due to node mobility and terrain size restrictions.

MANETS performance analysis studies have used (i.e. as recommended by IETF manet working group [IETF97]) quantitative performance metrics such as Packet Delivery Ratio (PDR), Normalized Routing Load (NRL) and Mean end-to-end Delay.

Unless otherwise specified, the three quantitative performance metrics are used in subsequent chapters.

1. *Packet delivery ratio*: This is the ratio of data packets successfully delivered to the number of data packets sent by the sources.

2. *Normalized Routing load*: This is the ratio of the total number of routing packets generated to the number of data packets successfully delivered to destination. Each hop wise transmission of a control packet is counted as a one transmission.

3. *Mean end-to-end delay*: The delays caused by latency, buffering, queuing, retransmission and route discovery are all included in this performance analysis. This delay is measured in seconds.

2.8. Literature Survey

MANETS have gone through tremendous research activity within last decade and many new protocols have been added to IETF MANET working group standardisation. Due to their versatility, MANETS have become focus of attention for researcher. Many variants of wireless adhoc networks such as Vehicular Adhoc Networks (VANETS), Wireless Sensor Networks and Wireless Mesh Networks etc. have become reality in today's world. However, through literature survey, it has been reflected that a majority of simulation based routing performance studies have used simplistic propagation environment. While *ns-2* remains the first choice as a simulation tool among MANETS research community [Kurkowski05], it has been noticed that majority of the published result (using *ns-2* tool) have relied upon default propagation model (i.e. TRG model) for wireless channel selection. There have been various other urban propagation models implemented into *ns-2* simulation environment [Cavilla07] [Stepanov08], but not the ITU-R models. Gruber *et al* [Gruber04] have implemented the COST-231-Walfisch-Ikegami model (COST-WIM) [Cichon99] (i.e. similar to the one described in Section

2.6.4 “Propagation over roof-top for urban areas”) into *ns-2* environment, however this model has some limitations in typical MANETS scenarios such as antenna height and frequency limitations (i.e. $f \leq 1800$ MHz, $h_t \geq 4$ m). Furthermore, it has been reported in literature that the COST-WIM model does not give good performance if antenna heights are less than rooftop level [Mustafa09]. Mangel *et al* [Mangel11] have compared the ITU-NLoS model (considering corner loss regions) with measurements from IEEE 802.11p radios (in inter vehicular street corner communication scenario) at 5.9 GHz frequencies and have stated, “Only the ITU-R P1411-5 2-16 GHz and the Toyota model come close to the measurements in this scenario”. Furthermore, comparing COST-WIM with ITU- LoS & NLoS urban path loss models, the ITU-R models include a broader range of parameter values (i.e. antenna height from 1.5 to 3 meters and frequency range from 300 MHz to 3000 MHz) which is more practical for MANETS scenarios. So by considering these facts, the ITU-R models were incorporated into the *ns-2* environment. Further literature survey will be mentioned in subsequent chapters.

Chapter 3

A Comparison of MANET Routing Performance using Different Realistic Propagation Models

3.1. Introduction

This chapter emphasizes the importance of the physical layer and its impact on network performance in MANETS. This chapter has been divided in three sections. The first portion (section 3.2-3.5) of this chapter investigates the impact of slow and fast channel fading for changing number of nodes and mobility patterns. Using network simulator *ns-2.34*, log normal shadowing (slow fading) and Rayleigh (fast fading) channel conditions have been analyzed with a variety of synthetic mobility patterns such as RWP, RPGM, MG and GM. The analysis is undertaken in a fixed area of 750x750 meters varying the number of nodes from 10, 20, 30, and 40 to 50. The resulting network performance is then compared with other studies, which used simplistic radio propagation models.

The second portion (section 3.6-3.8) of this chapter enhances the capabilities of *ns-2* by adding various path loss models (i.e. ITU LoS model, Green Obaidat Adhoc LoS model [Green02]) and the results from there were then compared with those produced using the TRG path loss model.

The third portion of this chapter covers the use of obstacle aware mobility environment in conjunction with modified TRG, ITU-R and Shadow fading conditions in *ns-2* simulation settings.

3.2. Network performance with slow and fast channel fading and different mobility patterns

Network simulator *ns-2* has been used for the evaluation of routing protocols and network performance in the majority of the reported MANET studies [Kurkowski05]. Furthermore, a majority of routing protocol studies has used simplistic radio propagation models for simulation analysis of network performance. In an urban area, where MANET applications are most likely to be deployed, using a simplistic propagation model may not represent the real wireless channel effects caused by reflection, diffraction, scattering and shadowing phenomena. Typically, multipath propagation and hence fading is very important for the urban case. Since fading can affect whether a node can communicate with adjacent nodes, this can have a significant effect on network performance. This study investigates the AODV protocol under slow and fast fading conditions with four different mobility models.

Signal fading arises from the constructive and destructive addition of the multipath components. Multipath results in both slow and fast fading [Haykin05]. Fast fading is said to occur if the channel impulse response changes rapidly within the symbol duration. Slow fading occurs when the coherence time of the channel is large relative to the delay constraints of the channel. Various distribution functions have been used for modelling fading in the wireless communication channel. This study uses the Nakagami (set as Rayleigh) distribution as a fast fading model and Lognormal shadowing as a slow fading model. Typically, two types of fading (Ricean or Rayleigh) are found between wireless links depending upon the geometric conditions. Rayleigh fading occurs where there is no line of sight (NLOS) between the transmitter and receiver. The Rayleigh distribution is a special case of

Nakagami distribution where $m = 1$ (see Equation 2.23) [Chen07]. For higher values of m (i.e. $m > 1$); the fluctuation of the signal strength reduces (.e. less severe fading) compared to Rayleigh fading.

There have been some studies made on the impact of fading in MANETS. In [Schmitz04] the authors introduce and discuss the impact of Topology Change Rate parameter (due to mobility and wireless power fluctuation) and its impact on network performance. Impact of RWP mobility with respect to link stability has been analysed in Schmitz's work. Jingfang *et al* [Jingfang09] have analysed the performance of AODV in Nakagami fading conditions for a static adhoc network of 24 nodes and changing the node density level for low (4 nodes), medium (9 nodes) to high (24 nodes) densities. In [Naseef10], the author has discussed the impact of fading on RWP mobility model with varying speed and pause time. However, network scalability with various mobility patterns has not been discussed in literature in context of slow and fast fading effects. This study covers the performance of AODV under fading condition with varying mobility patterns.

Figure 3.1 shows the probability of reception under slow and fast fading environment with increasing communication distance among nodes used in this simulation scenario (i.e. Tx Power 8.6 dBm, Rx_Threshold -84.5 dBm). It is evident that the node suffers with poor reception probability if the communication channel behaves like Lognormal shadowing model (i.e. slow fading environment).

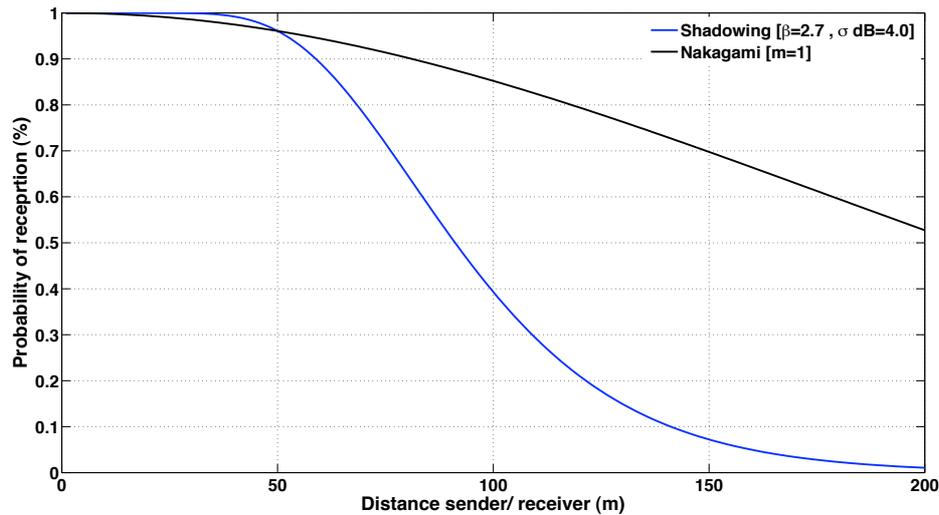


Fig.3.1- Probability of successful reception under slow/fast fading environment

3.3. Mobility scenario

Four synthetic mobility patterns (i.e. RWP (random), GM (temporal dependent), RPGM (spatial dependent) and MG (geographic dependent)) are used in this simulation analysis. Example node distributions for each model used in this simulation work are given in Figure 3.2. It is evident that RWP exhibits non-uniformity of node distribution within the network area with high clustering in the centre. Where as in GM model, nodes are more scattered towards the boundary in the simulated area. In MG, the nodes move in restricted lanes. So, although moderately evenly distributed on a 9x9 (each lane apart by 75 meters) lane grid, there are some points where there are large distances between nodes. With RPGM model as expected, nodes seem to have close inter & intra group interactions.

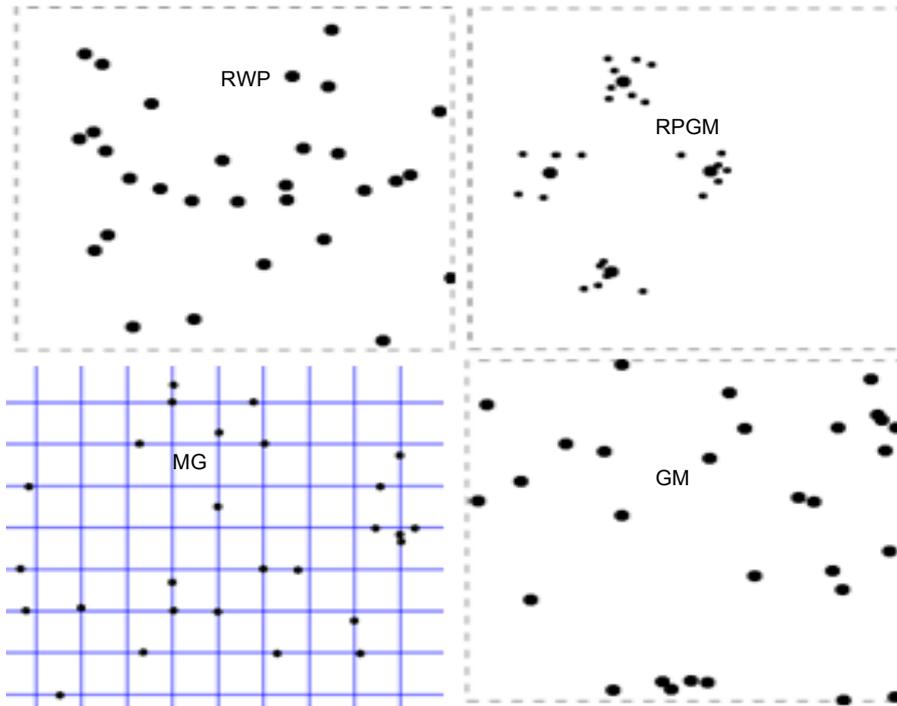


Figure 3.2: Snapshots of mobility models with 30 nodes

Figure 3.3 shows the average node connectivity (based upon transmission range and distance to other nodes) calculated for all mobility models used in this study with 160m-transmission range. It is apparent that RPGM mobility model shows high node connectivity due to grouped movement pattern whereas MG mobility has least connectivity and nodes may experience more broken communication links with this mobility behaviour (see Figure 3.2).

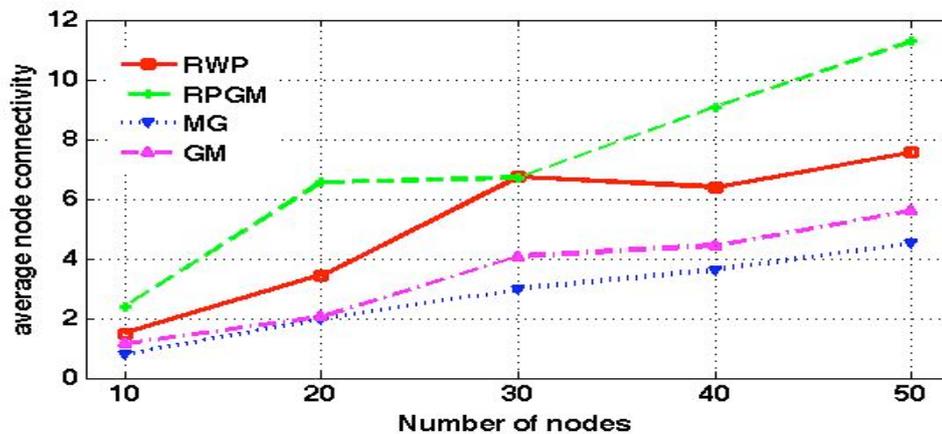


Figure 3.3: Average connectivity among nodes for 100 sec simulation run with zero pause time.

3.4. Simulation Environment

We used BonnMotion tool [Bonnmotion09] to generate mobility files for different mobility patterns in a fixed area of 750 X 750 meters. The node density was varied by changing the number of nodes in the fixed simulation area from 10 to 50 in steps of 10 nodes. We used IEEE 802.11b equipped radios with Omni directional antennas (height of 1.5m) and a receiver threshold of -84.5 dBm with a maximum transmission power of 8.6 dBm at 11 Mbits/s data rate. Each result is an average of five simulation runs (i.e. a normal practice in simulation based routing protocols performance analysis studies [Valery05], [Lee03]) with identical input parameters but with different random seed. Higher number of simulation runs may lead to prevent statistical errors such as due to initial positioning of nodes and particular mobility trace impact on routing protocol performance. Packet Deliver Ratio analysis with higher number of simulation runs (i.e. 10 & 15) have been compared in Section 3.5.1. Random traffic connections of Constant Bit Rate (CBR) traffic with a maximum of 20 connections and a rate of 8 packets sec^{-1} along with a packet size of 512 bytes were used between communicating nodes. CBR is the most common traffic type used in *ns-2* based MANET simulations generated through *setdest* (a traffic generation utility provided by *ns-2*). During CBR transmissions, the data rate remains constant (hence the name CBR) that may not be very useful for simulation of multimedia traffic (i.e. audio video traffic). Some of the simulation parameters are given in Table 3.1.

Table 3.1: Simulation parameters with varying node density

Parameter	Value
Simulation time	100 secs
Area size	750x750 m
Mean speed	1.5 m sec ⁻¹
Traffic type	CBR
Packet size	512 bytes
Connection rate	8 pkts sec ⁻¹
Channel frequency	2.4 GHz
Lognormal shadowing	$\beta = 2.7$
Outdoor urban area [Rappaport, 1996]	$\sigma_{dB} = 4$
Transmitter power	8.6 dBm
Tx and Rx antenna Gain (Gt=Gr)	1
Received power threshold (RXThreshold)	-84.5 dBm
Carrier sense threshold (CSThreshold)	-84.5 dBm

For Nakagami channel condition, we used the parameters as shown in Figure 3.4. These parameters were selected because they model a realistic urban channel for adhoc networks [Khan09].

```

Propagation/Nakagami set use_nakagami_dist_ true
Propagation/Nakagami set gamma0_ 2
Propagation/Nakagami set gamma1_ 2
Propagation/Nakagami set gamma2_ 2
Propagation/Nakagami set d0_gamma_ 200
Propagation/Nakagami set d1_gamma_ 500
Propagation/Nakagami set m0_ 1.0
Propagation/Nakagami set m1_ 1.0
Propagation/Nakagami set m2_ 1.0
Propagation/Nakagami set d0_m_ 80
Propagation/Nakagami set d1_m_ 200

```

Figure 3.4: ns-2 code fragment for Nakagami urban environment channel model.

Here in *ns-2* implementation, gamma values (i.e. *gamma0*, *gamma1* & *gamma2*) define the radio signal average attenuation over distance with respect to Ω function. Where as *d0_gamma* and *d1_gamma* are the distances where gamma values are discontinued. *m* values (i.e. *m0*, *m1* & *m2*) define the signal fading corresponding to *m* function with distances (i.e. *d0_m* & *d1_m*) where the gamma value discontinues.

3.5. Result Discussion

Simulation results are discussed in the following section.

3.5.1. Packet delivery ratio

Figure 3.5 shows the PDR under fast and slow fading conditions with respective standard deviation values given in Table 3.2. The PDR for AODV is significantly better when the mobility behaves like RPGM under both fading conditions. In RPGM mobility model, nodes tend to move in-group formations and thus have close relation with each other through group leader, and hence has a positive influence on the performance of the routing protocol. However, for RPGM mobility pattern, CBR traffic connections were divided equally for inter and intra group communications. This was important as high intra group communication will result in high network performance (i.e. nodes only communicating with nearby nodes in the same group) but may not be very realistic in real world group mobility scenarios. Furthermore in RPGM mobility, strict group formations (i.e. nodes do not change groups) were implemented with a maximum of 30 meters deviation of group members from group leaders. In [Bindral10], the authors have used RPGM with 50 nodes resulting in an average PDR for AODV of above 98% with 1000 x 1000 meters terrain size. Whereas with this study, the PDR with Nakagami and Shadowing models is 70% and 60% respectively even with a smaller terrain. Although RPGM shows higher connectivity among nodes (see Figure 3.3), this considerable difference in performance shows the significance of appropriate physical layer modelling for MANETS analysis. AODV performs better under Nakagami fading conditions for all mobility patterns since Shadowing conditions significantly impair the channel quality and hence the protocol

performance. For MG and GM mobility patterns, the PDR for AODV generally improves with increasing node density under both fading environments. This is due to more neighbouring nodes available in a multihop network environment. Under slow fading conditions, the performance of the AODV is not adequate for communication as majority of packets have been lost in most of the scenarios. This is significant as most of the protocol performance evaluation studies ignore the real channel fading environment and produce over-optimistic results.

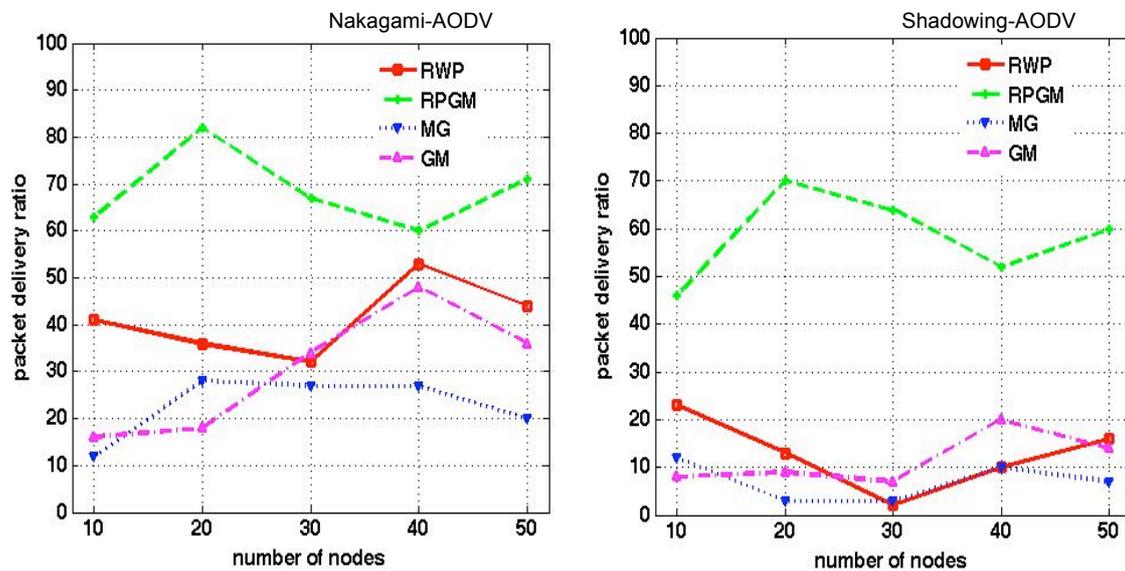


Figure 3.5: packet delivery ratio vs. number of nodes

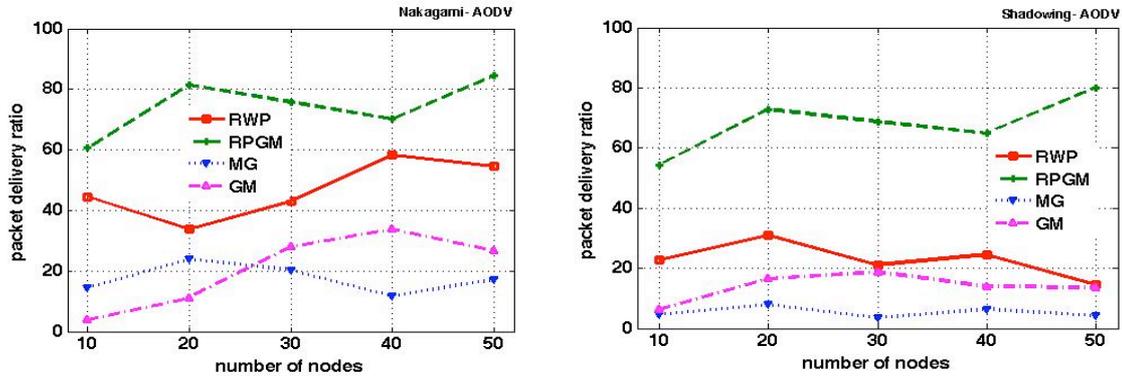
	Nakagami					Shadowing				
	10	20	30	40	50	10	20	30	40	50
RWP	13	10	10.73	6.48	8.29	9.52	3.96	4.82	9.34	6.05
RPGM	17.96	13.2	11.18	5.8	6.14	18.14	11.94	12.71	4.27	10.58
MG	9.1	12.5	10	7.2	3.78	5.49	5.44	3.71	2.4	3.4
GM	10.28	9.44	8.55	4.5	11.18	7.42	6.6	3.84	2.51	8.01

Table 3.2: Standard Deviation (STD) for AODV-Nakagami and AODV-Shadowing PDR results

Figure 3.6 shows PDR results for higher (i.e. 10 & 15) number of simulation runs with respected STD values shown in Tables 3.3 & 3.4. Comparing these results with Figure 3.5 (i.e. for 5 simulation runs), the common emerging

pattern is that MANET performance is better under slow and fast fading conditions if mobility behaves like RPGM model.

Packet delivery ratio vs number of nodes – 10 simulation runs



Packet delivery ratio vs number of nodes – 15 simulation runs

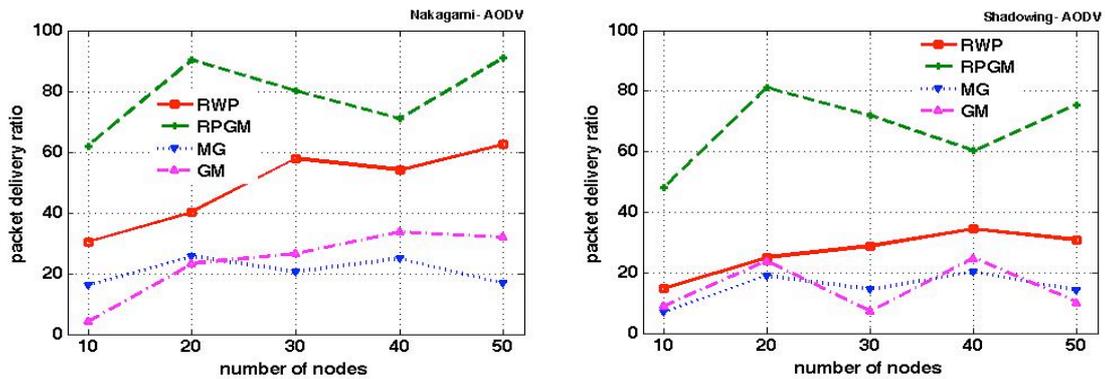


Figure 3.6: PDR vs number of nodes with 10 & 15 simulation runs

	Nakagami					Shadowing				
	10	20	30	40	50	10	20	30	40	50
RWP	14.4	12.3	6.8	7.81	9.47	5.1	6.96	3.94	7.3	6.77
RPGM	16.8	8.48	8.18	5.8	8.32	19.3	14.62	11.2	4.33	8.25
MG	13.8	11.1	10.4	6.2	9.78	2.54	7.6	3.35	4.02	4.85
GM	2.4	6.31	7.14	7.48	10.6	2.91	3.53	7	2.44	8.2

Table 3.3: Standard Deviation (STD) for AODV-Nakagami and AODV-Shadowing PDR results (10-simulation runs)

	Nakagami					Shadowing				
	10	20	30	40	50	10	20	30	40	50
RWP	16.8	9.17	7.22	7.35	8.57	8.48	4.1	3.68	8.65	6.04
RPGM	16.6	9.45	10.6	4.95	6.22	18.6	10.08	15.1	3.79	11.48
MG	14.7	11.6	10.5	8.5	7.86	3.21	6.66	3.93	3.32	4.44
GM	3.86	7.91	6.78	8.18	9.09	4.4	8.1	3.3	6.72	8.11

Table 3.4: Standard Deviation (STD) for AODV-Nakagami and AODV-Shadowing PDR results (15-simulation runs)

In case of RPGM mobility distribution, as half (i.e. 10) of the traffic connections are setup for intra group sessions and affects positively on overall network performance. Furthermore, GM and MG mobility have negative impact on AODV performance under both fading channel conditions. Moreover, Impact of slow fading environment (such as Lognormal Shadowing conditions) is more severe on network performance than fast fading conditions (such as with Nakagami fading channel).

3.5.2. Normalized routing load

From Figure 3.7, it can be readily observed that AODV suffers with considerably higher routing load with increasing node density under both fading conditions. Under fading conditions (either shadowing or Rayleigh), most of the packets are dropped because either interface queue is full or there is no route available when the transmitting node is waiting for an available route. Due to the random power fluctuations in the signal level caused by multipath propagation effects simulated here with Nakagami and Shadowing models, a route found in a route discovery process may not remain a valid route. With RWP mobility model, increasing node density increases the neighbour count and that may increase the probability of collisions, which leads to more retransmission attempts, and thus increases the routing load significantly. NRL is an important factor to determine the scalability of routing protocol in MANETS. Higher routing load will definitely lead to higher delay and will consume more battery power in a mobile environment with limited resources. With the broadcast nature of AODV for new route discovery, neighbouring nodes tend to receive multiple copies of same Route Request and thus increase the routing load sharply. With the

RPGM mobility model, AODV shows consistent results for both fading conditions. However, the routing load is high for lognormal shadowing conditions with the MG mobility model. This is due to the fact that nodes in MG model follow horizontal and vertical routes and move in restricted areas and can therefore be out of transmission range of other nodes (i.e. low average node connectivity as seen in Figure 3.3). This can lead to higher routing overheads and delays and to a lower PDR.

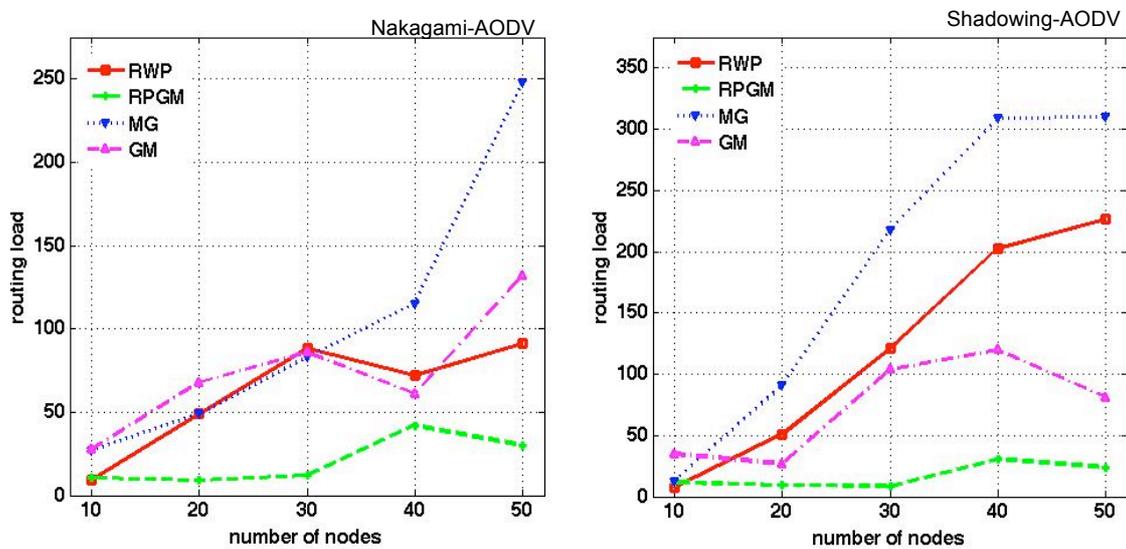


Figure 3.7: routing load vs. number of nodes

Nakagami	10	20	30	40	50	Shadowing	10	20	30	40	50
RWP	8.6	18	42.77	21	43	RWP	4	7	43	57	67.6
RPGM	2.72	2.97	4.92	2.3	2.07	RPGM	2.86	1.60	3.23	3.56	2.12
MG	14	16.8	59	57.43	51.12	MG	3	44	57	86	109
GM	12.9	30	34.4	19	44	GM	6.9	13	42.4	19	44.8

Table 3.5: Standard Deviation (STD) for AODV-Nakagami and AODV-Shadowing RL results

3.5.3. Mean end-to-end delay

From Figure 3.8, it is evident that the mean delay is very high when the radio channel behaves like a lognormal shadowing fading environment. In this

study, AODV suffers with radically higher delay under MG and GM mobility patterns. Increasing node density generally decreases the mean delay as nodes possibly have shorter routes available as more nodes are in transmission range of each other. Again AODV performs notably well for the RPGM model for both Rayleigh and Shadowing fading. This may result from the close proximity of nodes in each group and hence within transmission range.

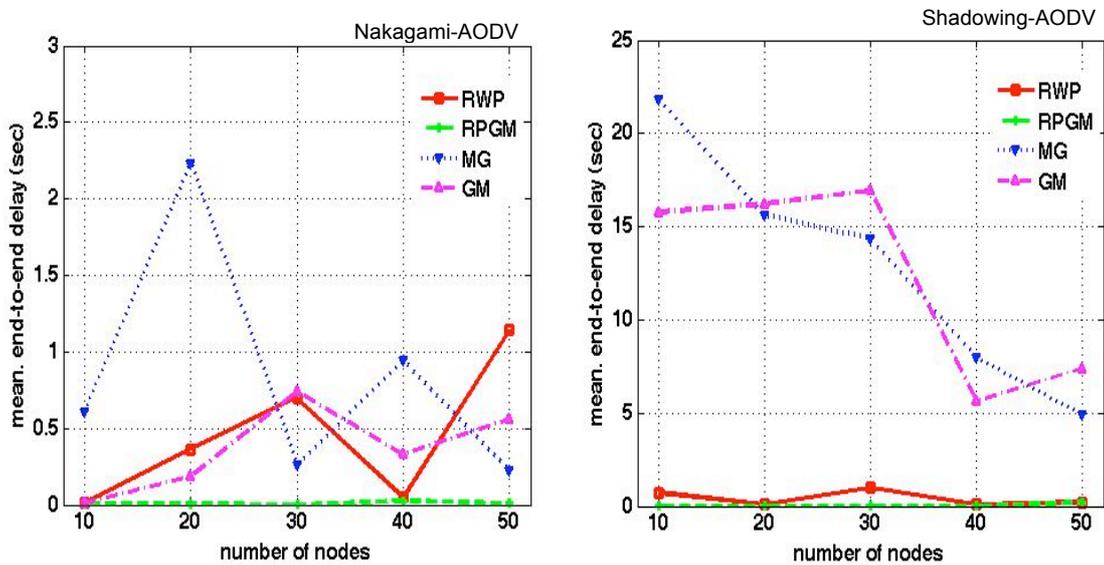


Figure 3.8: Mean end-to-end delay vs. number of nodes

Nakagami	10	20	30	40	50	Shadowing	10	20	30	40	50
RWP	0.37	0.96	0.78	0.62	0.51	RWP	1.16	0.612	0.531	0.206	1.07
RPGM	0.117	0.07	0.041	0.005	0.025	RPGM	0.092	0.024	0.877	0.013	0.073
MG	0.572	1.12	1.1	0.539	0.812	MG	4.68	2.06	5.44	2.6	1.73
GM	0.086	1.01	0.42	0.909	1.17	GM	3.68	4.09	4.42	0.909	1.67

Table 3.6: Standard Deviation (STD) for AODV-Nakagami and AODV-Shadowing Mean Delay results

3.6. Effects of ITU path loss models in a multi mobility environment

In this section, we compare the performance of two widely used routing strategies for MANETS, i.e. Adhoc On-demand Distance Vector (AODV) and

Dynamic Source Routing (DSR) in a multi mobility environment. Using the *ns-2* simulator, a variety of mobility models are incorporated in the same scenario (e.g. two group movements and three random mobility patterns) to analyse the performance of an ad-hoc network with 100 nodes. Two new propagation loss models (i.e. GOA- LoS and ITU-LoS in street canyons (ITU-LoS)) were incorporated into *ns-2* and the results from there were then compared with those produced using the TRG path loss model.

The analysis is undertaken in a fixed arbitrary rectangular area of 1600x1000 meters varying the pause time of nodes from 0 sec to 500 sec in steps of 100. The resulting network performance is then compared with other studies, which used simplistic radio propagation models [Mittal09], [Tuteja10]. To the best of our knowledge, no other study has analysed outdoor MANETS performance with ITU-LoS and GOA-LoS propagation loss models.

There have been different propagation models discussed in context of *ns-2* simulations [Stepanov08], [Eltahir07]. In [Eltahir07], the author discusses the impact of Free Space, TRG and Shadowing model on MANETS in *ns-2* simulation environment using MG mobility model. In [Stepanov08], the authors introduce a ray-tracing model in *ns-2* environment with pre-calculated signal strength measurement using WinProp [Winprop10] tool. However, the mobility has not been considered. So, there is still requirement for a more comprehensive mobility and propagation model implementation for MANET scenarios. So we have added ITU & Green-Obaidat model for LoS scenarios in *ns-2* simulations and tested the network performance in hybrid mobility conditions.

Figure 3.9 shows the received signal strength plot with varying communication range among nodes. With -84.5 dBm receiver sensitivity threshold used in our simulation, the communication range extends highest with TRG model (i.e. 250 meters) and lowest for ITU- UHF urban LoS model (about 110 meters). This is expected as there are extra losses that have been added into ITU-LoS model due to fading conditions found in urban structures.

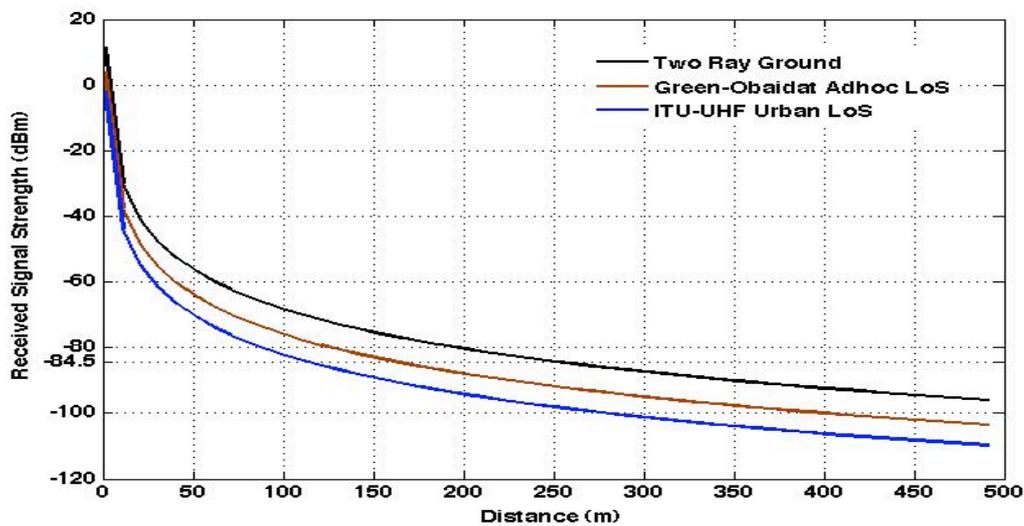


Figure 3.9: Received signal strength vs communication distance

3.7. Mobility scenario

A hybrid multi mobility environment is used for an ad-hoc network of 100 nodes divided equally in 5 different mobility patterns such as Random WayPoint (RWP), Random Direction (RD), Levy Walk (LW), Reference Point Group Mobility (RPGM) and String model (SM). Figure 3.10 shows the movement behaviour of nodes under individual models and the mix mobility environment (bottom right) used for simulation. These snapshots were taken after 250 sec in a 500 sec simulation run for all models. It is evident that RWP exhibits non-uniformity of node distribution within the network area with high

clustering in the centre. In case of RD, nodes are more scattered in the simulation field. Where as with LW pattern, nodes tend to stay in certain parts of the simulation area. With RPGM and SM mobility behaviours, nodes strictly follow the motion of their respective group leaders in two different manners.

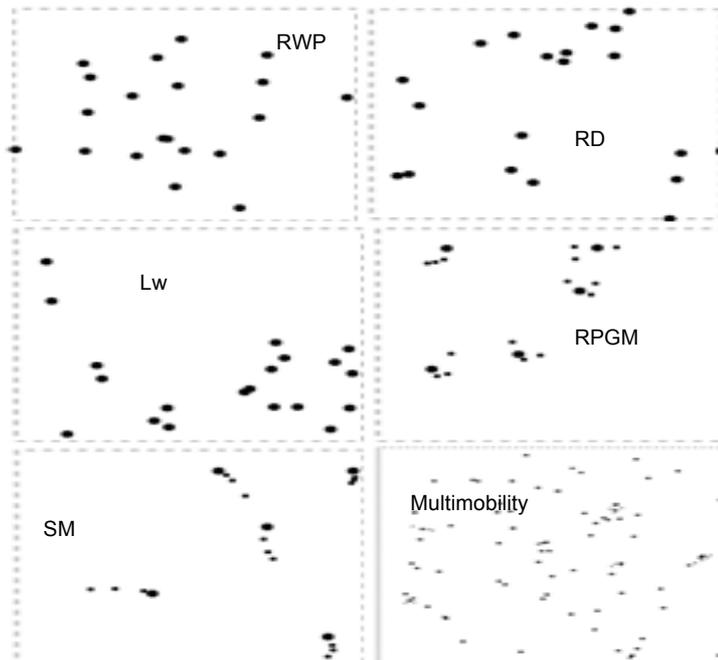


Fig 3.10: Snapshots of mobility models with a) 20 nodes for individual models & b) 100 nodes for multi mobility model.

3.8. Simulation Environment & Results

The main aim of this study is to analyse the impact of propagation loss in a multi mobility environment (i.e. adding various mobility patterns in same scenario) on routing performance for an ad-hoc network. To evaluate the performance of two protocols, we took the following scenario; we changed the nodal pause time (i.e. mobility level) from 0 sec (i.e. continuous motion) to 500 sec in steps of 100 for a pedestrian environment. Mobile nodes were initially distributed randomly on the simulation field with boundary reflection

attribute (i.e. nodes will stay in the simulation area during the whole simulation period). A cutoff period of 1000 secs (i.e. by generating 1500 secs mobility file and using last 500 secs mobility trace for simulation) was used to stabilize mobility behaviour of nodes. We generated ten mobility files for each mobility scenario. Each result is an average of ten simulation runs with identical input parameters but with a different random seed. We used IEEE 802.11b equipped radios with Omni directional antennas (height of 1.5 m) and a receiver threshold of -84.5 dBm with a maximum transmission power of 4.7 dBm at 11 Mbits/s data rate. Some of the simulation parameters are given in Table 3.7.

Table 3.7: Simulation parameters with varying pause time

Parameter	Value
Simulation time	500 secs
Area size	1600x1000 m
Traffic type	CBR
Packet size	512 bytes
Max. number of Traffic sources	16
Rate	8 pkts/sec
Channel frequency	2412 MHz
Mobility environment	Multi mobility (5 sub models)
No. of nodes	100 (divided equally in 5 sub models)
Transmitter power	4.7 dBm
Tx and Rx antenna Gain (Gt=Gr)	1
Rx and CS Threshold	-84.5 dBm
CP Threshold (Signal to interference ratio)	10 dB

3.8.1. Packet Delivery Ratio

Figure 3.11 shows the PDR under various propagation conditions for AODV and DSR with standard deviation values (shown in table below). The PDR for AODV and DSR is better when the channel behaves like TRG model. AODV performs better than DSR under different propagation loss situations. This is mainly due to the node density issues related with DSR (i.e. will be

discussed further in Chapter 4). The performance of AODV is generally poor if the communication channel acts like ITU-LoS model. This is largely because of the extra loss incorporated into this model due to multipath effects typically found in urban environments. This is significant as most of the protocol performance evaluation studies ignore the real channel fading environment and produce over-optimistic results.

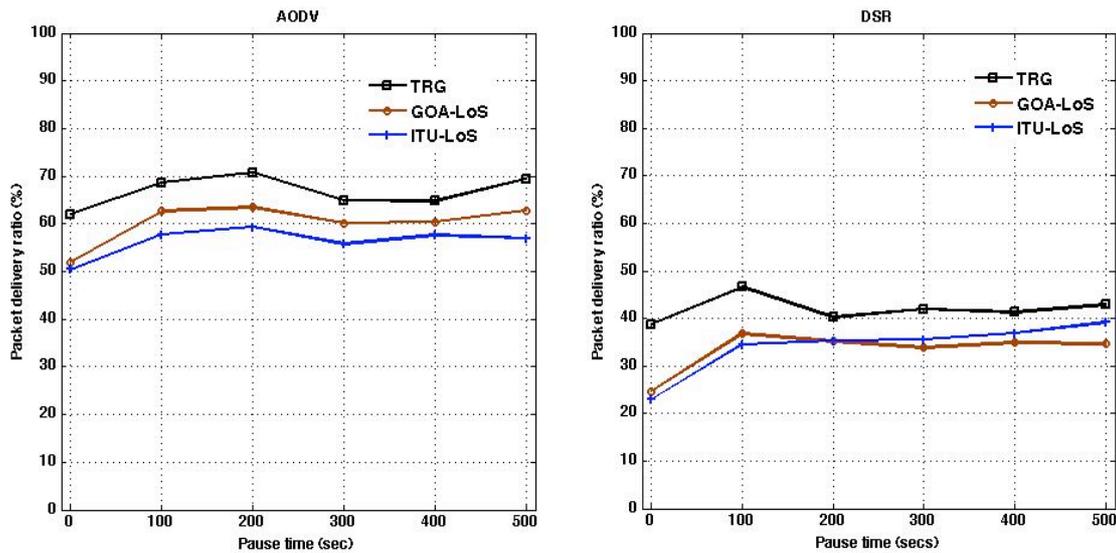


Figure 3.11: Packet delivery ratio vs pause time

AODV	0	100	200	300	400	500	DSR	0	100	200	300	400	500
TRG	8.7	8.2	6	6.6	8	6.63	TRG	9.8	8.4	5.48	9.1	11.6	5.6
GOA-LoS	7.5	8	4.1	6.4	9.3	8.53	GOA-LoS	8	11.9	5.79	7	6.5	10.3
ITU-LoS	8.6	5.7	4.8	6.7	5.4	8.52	ITU-LoS	6	9.7	5.79	6.4	8	11.6

Table 3.8: Standard Deviation (STD) for AODV and DSR PDR results

3.8.2. Normalized Routing Load

From Figure 3.12, it can be readily observed that AODV and DSR suffer with considerably higher routing load under ITU-LoS and GOA-LoS propagation conditions with zero pause time (i.e. high mobility). Again under poor transmission conditions (i.e. high propagation loss environment), most of the packets are dropped because interface queue is full when the transmitting node is waiting for an available route. Also with broadcast

nature of AODV and DSR for new route discovery, neighbouring nodes tend to receive multiple copies of same Route Request and thus increase the routing load sharply. Mobility causes more frequent topology changes and hence the network suffers with high routing load. This is critical as higher PDR and lower routing load is always desirable in a bandwidth and battery power constrained environment.

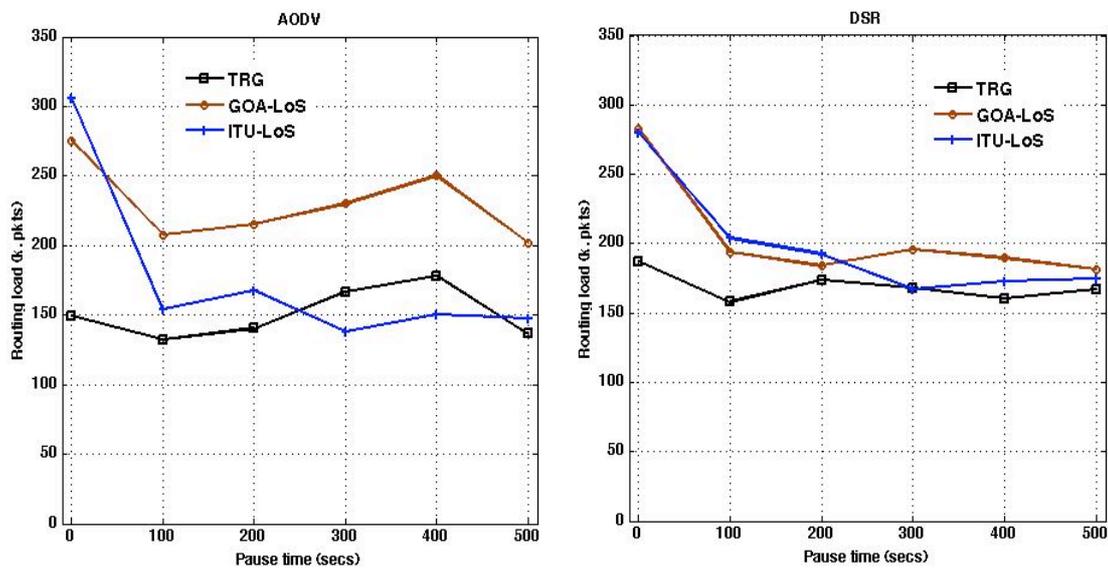


Figure 3.12: Routing load vs pause time

	AODV						DSR					
	0	100	200	300	400	500	0	100	200	300	400	500
TRG	2.8	2.9	2.2	2.4	1.8	1.3	5.2	5	3.8	4.94	5.7	3.2
GOA-LoS	3.9	3.3	2.5	3.6	3.1	2.8	14.3	8.5	4.5	5.46	4.1	5.5
ITU-LoS	4.8	2.9	2.3	2.1	2.1	3	13	6.9	4.7	3.83	4.8	8.8

Table 3.9: Standard Deviation (STD) for AODV and DSR RL results

3.8.3. Mean end-to-end delay

From Figure 3.13, it is evident that the mean delay is very high when the radio channel behaves like an ITU-LoS or GOA-LoS environment for DSR protocol. Generally new route requests are more common in AODV (i.e. only one route per destination available in route table) as DSR uses

aggressive caching technique and usually multiple routes are available to destination in the node cache. But due to poor physical layer conditions (i.e. ITU-LoS or GOA-LoS environment), the benefit of cache seems to have been lost as DSR tries its full cache before initiating a new route discovery and this property of DSR increases mean delay significantly. With higher routing load and mean delay, the network performance is significantly poor if the channel conditions are like ITU-LoS model for AODV and DSR.

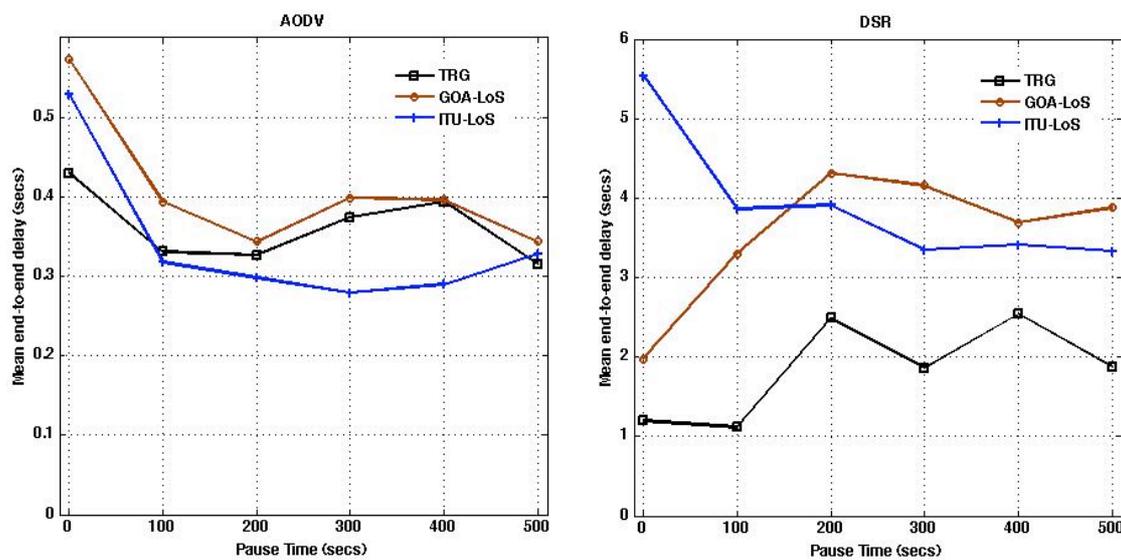


Figure 3.13: Mean end-to-end delay vs pause time

AODV	0- Pause	100- Pause	200- Pause	300- Pause	400- pause	500- pause	DSR	0- Pause	100- Pause	200- Pause	300- Pause	400- pause	500- pause
TRG	0.213	0.12	0.104	0.117	0.120	0.083	TRG	1.01	0.336	1.14	0.711	1.09	0.77
GOA- LoS	0.163	0.132	0.0853	0.11	0.123	0.166	GOA- LoS	0.42	1.48	1.27	1.04	1.14	0.60
ITU-LoS	0.124	0.135	0.079	0.090	0.083	0.127	ITU- LoS	1.37	1.28	1.33	1.09	0.83	1.25

Table 3.10: Standard Deviation (STD) for AODV and DSR Mean Delay results

3.9. MANETS Routing Performance Analysis in a terrain aware mobility and propagation environment

This study enhances the capability of *ns-2* by adding various propagation loss models (i.e. ITU-Non Line of Sight (ITU-NLoS)) model into street canyons and

combined path loss and shadowing model (C-Shadowing)) and compares the simulation results with the TRG and TRG (modified) model. The simulation study is conducted in a mobile environment with Random Way Point (RWP) mobility model and varying the no. of obstacles (i.e. buildings etc) in simulation field in order to analyze the impact of communication losses with increasing attenuation (i.e. due to obstacles) for various propagation loss models. The performance of Adhoc On-demand Distance Vector (AODV) routing protocol is analyzed in an adhoc environment with 20 nodes. *ns-2* simulation tool accommodates various routing, mobility and propagation features key to analyze the performance of MANETS. However, this tool considers flat terrain for simulation and does not accommodate geographical features that may affect the received signal strength at the receiver in real world scenarios. In [Jardosh05], the authors have introduced specialized mobility models, which restrict the mobility of nodes due to obstacles in the simulation area and some variations have been suggested in [Papageorgiou09] for *ns-2* environment. However the focus of their work is mainly the mobility aspect of the nodes. We have used the mobility model based upon obstacles as described by [Papageorgiou09] for this simulation work. Obstacles of various sizes with random positions in the network field have been introduced in a rectangular area of 1000x600 meters. By varying the number of obstacles in the simulation field, the performance of Adhoc On-demand Distance Vector (AODV) routing protocol has been analysed on the basis of various quantitative performance metrics. Moreover in [Jardosh05], the authors have discussed the modified Two Ray Ground model that accounts for signal attenuation between two nodes obstructed by a wall or

building and reduces the effective signal strength received at the receiver by a random value. However this aspect does not cover the increasing attenuation due to increase in obstacles (i.e. such as buildings) in the simulation area. Wu *et al* [Wu11] have introduced an obstacle-aware mobility model in *ONE* [Keränen09] (a Delay Tolerant Network (DTN) simulator) introducing obstacles of various shapes (i.e. round, hexagonal shapes etc) and results have been obtained for DTN. The propagation model used by [Wu11] is similar to the one mentioned in [Jardosh05]. In [Cavilla07], the authors have used the Attenuation Factor propagation model [Rappaport1996] in a constrained mobility environment that accounts for the number of walls between transmitter and receiver and calculates the attenuation based on rgb (i.e. colour) values among them. The primary objective of above mentioned works is the obstacle based mobility analysis with little attention to propagation perspective specifically with increasing obstacles. The propagation impact with varying obstacles has not been looked upon in details. So this work covers the shortcomings in that aspect and analyses the MANET performance with the effect of increased attenuation due to increased obstacles.

Figure 3.14 shows the various simulations environments used in this study with changing obstacles of random sizes from 0 (i.e. flat area) to 10 obstacles (i.e. urban dense area).

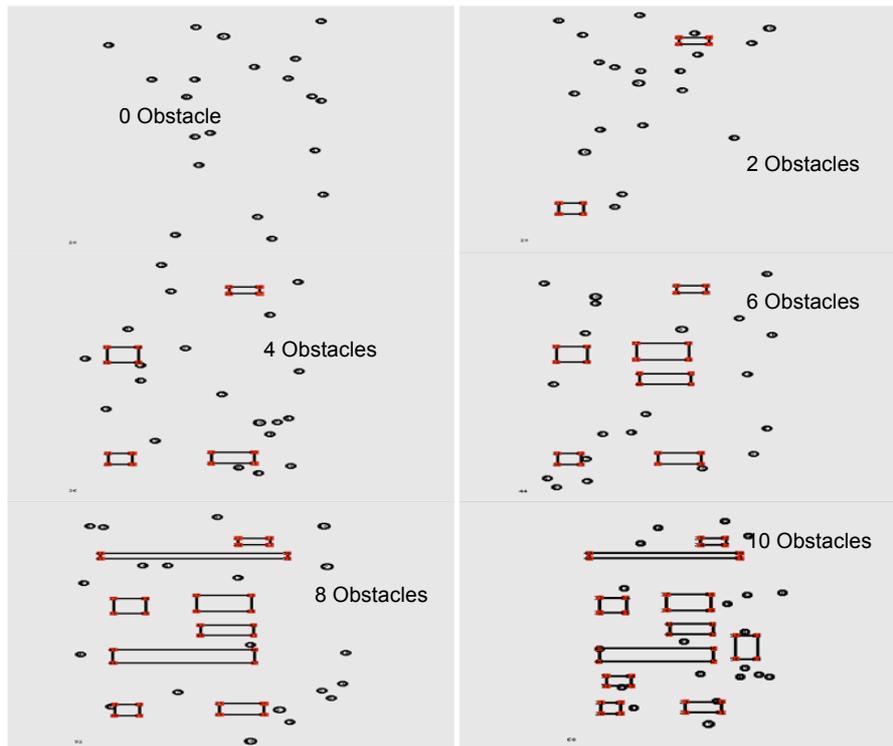


Figure 3.14: Simulation field with varying number of obstacles

3.10. Methodology

The main aim of this study is to analyze the impact of propagation loss with varying obstacle level in the simulation field. We have modified the TRG model, which counts the number of walls among communicating nodes, and apply the attenuation level in accordance with brick wall attenuation recommendations (i.e. 6 dB/wall) [Rappaport96] for an outdoor environment. Furthermore, a hybrid ITU propagation model ITU-LoS&NLoS has been used (i.e. depending upon node location relative to obstacles) along with Combined Shadowing (C-Shadow) model [Goldsmith05] into simulation environment. C-Shadow model is a combination of simplified path loss model with lognormal shadow fading [Goldsmith05]. We generated ten mobility files for each mobility scenario. Each result is an average of ten simulation runs with identical input parameters but with different random seed. We used IEEE

802.11b equipped radios with Omni directional antennas (height of 1.5 m) and a receiver threshold of -85 dBm with a maximum transmission power of 15 dBm at 11Mbps/s data rate. Some of the key simulation parameters used for this simulation work are shown below in Table 3.11.

Table3.11: Simulation parameters with varying obstacles

Parameter	Value
Simulation time	500 secs
Area size	1000x600 m
Mean speed	1.5 m sec ⁻¹
Traffic type	CBR
Packet size	512 bytes
Connection rate	8 pkts sec ⁻¹
Channel frequency	2.4 GHz
Mobility Model	Random Way Point
No. of Obstacles	0,2,4,6,8,10
Brick Wall attenuation (for TRG only)	6 dB
C-Shadowing	$\gamma = 2.7$ $\Psi_{dB}=4$ (for urban areas)
Transmitter power	15 dBm
Tx and Rx antenna Gain (Gt=Gr)	1
Received power threshold (RXThreshold)	-85 dBm
Carrier sense threshold (CSThreshold)	-85dBm

3.11. Results

Simulation results are discussed in the following section.

3.11.1. Packet Delivery Ratio

Figure 3.15 shows the PDR for different propagation loss conditions. The results indicate that all the path loss models (except TRG) show almost linear degradation in performance as the number of obstacles increases from 0 to 10 in steps of 2. Although the ITU-R and C-Shadow model do not accommodate obstacles in their method, the increasing obstruction level means that there is more possibility of NLoS conditions among communicating nodes which increases the uses of ITU-NLoS model during simulation run and hence nodes experience higher attenuation. Furthermore, increasing the number of obstacles decreases the movement area for nodes

(i.e. as nodes move only in available free space), which results in reduced mobility level and hence increases the possibility of more communication failures among nodes. It is clear from results that simple TRG model does not take into account the attenuation caused due to increasing obstacle in simulation environment and hence very little change in PDR is observed with this model. On the other hand, TRG-modified model decreases the received signal strength by 6 dB for each wall encountered in the communication path, which results in a more realistic simulation of the propagation, and hence decreasing the routing performance. Nodes experience more random power fluctuation in received signal strength with C-Shadowing model and hence network suffers with performance degradation. It has been observed that poor channel conditions (i.e. such as simulated through TRG-modified, ITU-R and C-Shadow model) shows higher fluctuation among results. As each result is an average of ten simulation runs, higher fluctuation among mean values can be realized through higher standard deviation values.

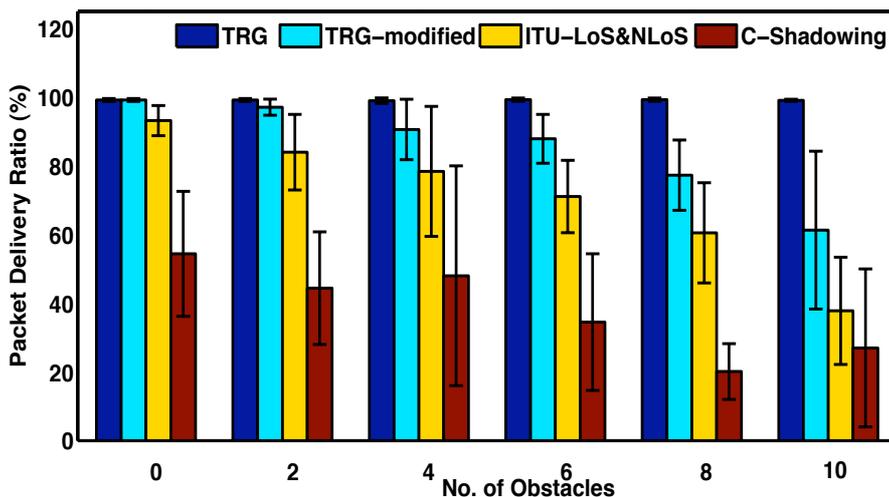


Figure 3.15: PDR vs No. of Obstacles

3.11.2. Normalized Routing Load

From Figure 3.16, it can be readily observed that AODV suffers with considerably higher routing load with increasing obstacles. Increasing the obstacles also increases the possibility of disconnections among nodes due to higher level of attenuation. As mobility gets limited with increasing obstacles, there is more possibility of link failures among nodes and hence this cause increases routing load significantly.

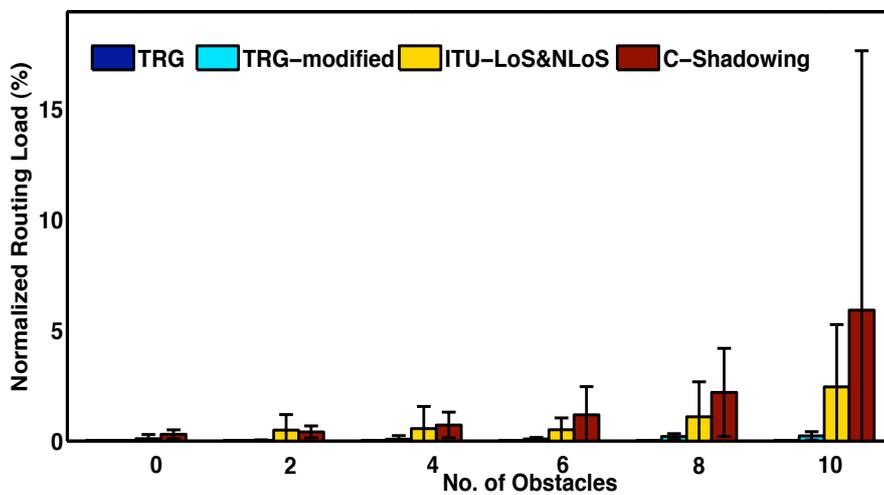


Figure 3.16: NRL vs No. of Obstacles

3.11.3. Mean end-to-end Delay

From Figure 3.17, it is evident that the mean delay is very high when the radio channel behaves like a C- shadowing fading environment. With increasing obstacles in the simulation environment, nodes experience less connectivity due to buildings etc and hence increasing routing load leads to longer communication delays. Again it is worth noticing that there is negligible change in Mean Delay with over-simplified model (in urban environment) such as TRG.

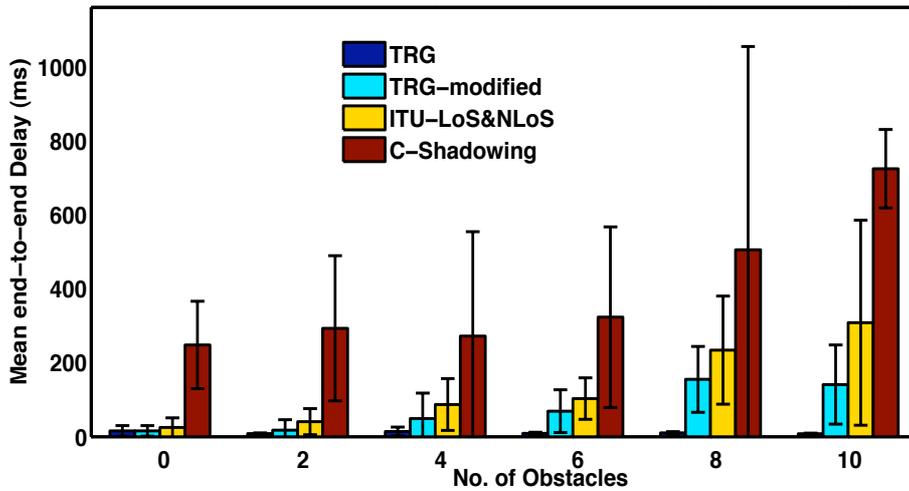


Figure 3.17: Mean Delay vs No. of Obstacles

3.12. Summary

This chapter focuses on the importance of appropriate physical layer modelling and its impact on the performance of AODV with various mobility scenarios. The extensive simulation study verifies that physical layer modelling and mobility patterns can have significant impact on routing performance in MANETS. The first section of this chapter compares the MANET performance in slow and fast fading environments. Slow fading conditions such as shadowing strongly impair the network performance. The performance of AODV is better under fast fading conditions even with NLOS environment such as Rayleigh channel. This study compares the produced results with the AODV performance analysed with TRG channel environment and confirms that the simplistic radio propagation modelling can overestimate the protocol performance so as expected will not produce realistic results for a heavily built up area. Mobility models can have a significant effect on the simulated performance of MANETS. For example, RPGM model seems to

lead to better AODV performance under slow and fast fading channels. For MG and GM mobility models, AODV suffers with low PDR, higher routing load, and increased mean delay for both fast and slow fading models. For vehicular ad-hoc networks in urban area, MG is likely to be a realistic mobility model (for pedestrian and vehicular mobility environment) and the low performance means that AODV may not be a suitable choice for such cases.

The second portion of this chapter compares the two LoS models (i.e. ITU-LoS within street canyons and GOA-LoS model) with the results from the TRG model. The network performance was analyzed with varying pause time to simulate various levels of mobility. Results suggest that the network performance is generally better if the communication channel behaves like TRG path loss model. Fading conditions strongly impair the network performance in urban scenarios. With increasing pause time (i.e. changing mobility level), DSR experiences significantly higher routing load and mean delay if the channel acts like GOA-LoS or ITU-R LoS model. This is predominantly due to node density issues related with DSR as node movements, network congestion and propagation loss effects invalidate the routes. Although DSR uses a route caching technique, the benefit of this seems to have been lost due to high mobility level. This study compares the produced results with the AODV and DSR performance analyzed with TRG channel environment and confirms that simplistic radio propagation modelling can overestimate the protocol performance so may not produce realistic results for a heavily built up area.

The third part of this chapter introduces the effect of obstacles on propagation into the simulation through modified TRG and ITU-LoS & NLoS model. The

results clearly show that increasing the number of obstacles increases the attenuation level among communicating nodes and has a significant impact on MANET performance.

Chapter 4

MANET Performances With Varying Node Mobility

4.1. Introduction

The previous chapter focused on the importance of appropriate physical layer modelling in MANETS. This Chapter investigates the mobility related effects in RWP and RPGM mobility patterns. The first portion of this chapter (section 4.2-4.7) investigates two MANET protocols (i.e. Ad-hoc On-demand Distance Vector routing (AODV) and Dynamic Source Routing (DSR) and examines their performance with different node densities and mobility levels using mobility models such as RWP and Random Way Point with Attractions (i.e. a variation of RWP (RWP-ATTR)).

The second portion of this chapter (section 4.7-4.10) investigates the effect of changing the leader's mobility behaviour in group movements. Four variants of leaders mobility patterns (i.e. LW, Prob-Rand, RD and RW) have been tested with DSR in a 75 node MANET environment.

4.2. Research Background

RWP is the most common mobility pattern used in MANET simulation environment. *ns-2* provides *setdest* utility (CMU Monarch extension) through which RWP based mobility files can be generated. RWP simple algorithm has been discussed in Chapter 2. However, RWP has some known characteristics, which affect the simulation results significantly and must be considered before simulation [Yoon03]. A well-mentioned issue is that nodes are not evenly distributed in the network field by this mobility model due to biasness of nodes

towards the centre of the simulation area [Bettstetter02]. This node density distribution results from the next destination selection by nodes. A node that moves from one point to another usually has to move through the centre resulting in clustering of nodes in the middle of simulation area. Many variations have been suggested by the researchers in this mobility model such as random walk, random direction, smooth random [Camp02], [Royer01], [Bettstetter01]. There is a large number of studies about the performance of routing protocols in MANETS for different scenarios [Johnson98], [Boukerche04], [Misra05], [Anuj10],[Reddy06] in the literature using RWP mobility model and analyzing AODV & DSR in *ns-2* environment. Misra and Mandal [Misra05] have described that the performance of reactive routing protocols is highly dependent upon the scenario. However, poor performance of DSR specifically with increasing node density (i.e. above 75 nodes) in RWP mobility environment have not been discussed in literature. It was observed during our simulation analysis that DSR suffers severely with performance degradation with the scenarios considered in our experiments. With increasing node density in a fixed area, the performance of DSR is affected very badly with all performance metrics taken into consideration for this study.

4.3. Random Waypoint with attraction points

This is a variation of the simple RWP model firstly introduced by [Bettstetter01], which allows the node density to be higher in any particular area of the network field. The Bonnmotion tool [Bonnmotion09] supports this feature in RWP by allowing nodes to move towards the destinations assigned as 'Attraction Points' in the simulation area more frequently. Both RWP and

RWP-ATTR can resemble the behaviour of mobility in downtown, university campus, and parks and playing field areas. In a university scenario attraction points can be defined as library, classrooms, labs and café.

Figure 4.1 plots the mobility metrics considered for RWP and RWP-ATTR mobility patterns. Using 250 meters transmission range and varying node density and pause time, the statistical analysis of two different mobility models have been performed. All calculations are done with 1000 sec simulation time and in an area of 500x500 m². The following two mobility metrics are used for mobility analysis.

1. Link Breaks: This is the total number of communication links dropped due to mobility effects.
2. Average Link Duration: Average time a link is established between all nodes. Links that go up after simulation starts and go down before simulation ends are considered in this parameter.

Links are defined here as communication path set up between nodes during simulation time. A link between two nodes exists if they are in communication range of each other. As pause time increases (i.e. mobility level decreases), the number of link breaks decreases sharply and the avg. link duration increases. This behaviour has positive impact on routing performance in MANETS (will be discussed further in details later). With zero pause time (i.e. high mobility) considered for increasing node density, there is a significant rise in link break occurrences if the mobility behaviour is like RWP mobility pattern. More link breaks result in lower PDR and higher NRL and Mean Delay for routing protocol performance.

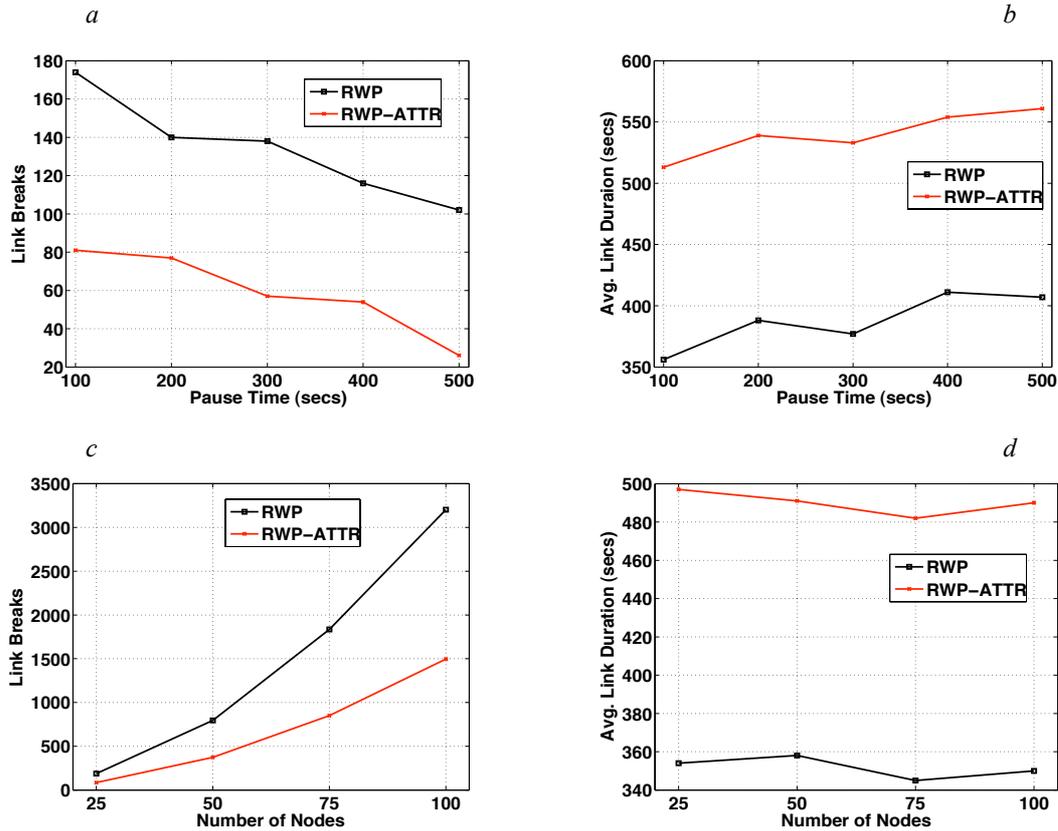


Figure 4.1: Mobility based Link Analysis of RWP & RWP-ATTR with 250 m transmission range
a) No. of Link Breaks vs Pause time (25 nodes) b) Avg. Link Duration vs Pause Time (25 nodes)
c) No. of Link Breaks vs No. of Nodes (0 Pause time) d) Avg. Link Duration vs No. of Nodes (0 Pause time)

4.4. Mobility models scenario generation

The following section describes the mobility scenarios files.

a. For Random Way Point movement patterns, mobility files were generated using 25,50,75 and 100 nodes with a minimum speed of 0.5 ms^{-1} and a maximum node speed of 1.5 m s^{-1} (average human walking speed) in an arbitrary simulation area of $500 \times 500 \text{ m}$.

b. For Random Way Point with attraction points, four arbitrary attraction points were chosen with the following parameters. Where the fourth attraction point has the highest probability of visit by nodes set as '2.5' and the first attraction point has the least probability set as '1'. These attraction points are set close to the edges of the simulation area in order to analyse the impact of non-uniform node distribution behaviour (i.e. nodes tend to cluster in the middle of

the simulation area [Bettstetter02]) of Random Way Point model on routing protocol's performance.

Table 4.1: Attraction point parameters for RWP-ATTR

Attraction point No.	X value (m)	Y value (m)	Visiting probability
1	100	100	1
2	400	100	1.5
3	100	400	2
4	400	400	2.5

Figure 4.2 shows the screen shot of both mobility models used in this section. It is apparent that nodes cluster in RWP mobility pattern in the middle of the simulation area while otherwise are more scattered with RWP-ATTR mobility scenarios.

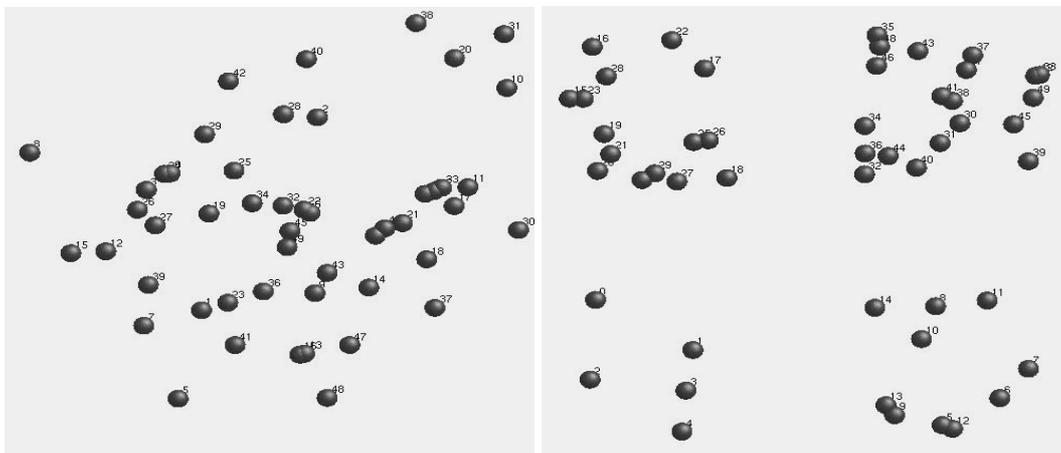


Figure 4.2: Node movement pattern with RWP (left) and RWP-ATTR (right) mobility models captured during 500 secs simulation run and with fifty nodes.

4.5. Simulation Environment

To evaluate the performance of two protocols, we took two scenarios, in the first the node density was varied by changing the number of nodes (n) in a fixed area (width, w & length, l), and in the second the nodal pause time was

varied. *ns-2* (version 2.33) was used for all simulation runs with the default routing protocol parameters. Each result is an average of five simulation runs with identical input parameters, but with different random seeds.

The key simulation parameters employed in simulating the effect of varying the node density are shown in Table 4.2. A flat area of 500x500 m is chosen with IEEE 802.11b equipped radios and with Two Ray Ground as a propagation model by taking into consideration both direct and indirect paths between communicating nodes. As found in Chapter 3, the use of TRG model is not likely to be suitable if dense urban area is selected for MANET deployment. A nominal radio coverage range of 250 m is chosen for these experiments. A zero pause time is used to simulate a mobility level with nodes that are continuously moving in the simulation area.

Table 4.2: Simulation parameters with varying node density

Parameter	Value
Protocols	AODV, DSR
No. of nodes	25,50,75,100
Area size	500x500 m
Avg. Speed	1 m s ⁻¹
Mobility Models	RWP, RWP (ATTR)
Traffic Type	CBR
Packet size	512 bytes
Rate	8 pkts sec ⁻¹
Queue Length	50
Pause Time	0 sec
No. of traffic sources	20
Transmission range (<i>r</i>)	250 m
Propagation path loss model	Two Ray Ground
Radio channel frequency	2.4 GHz
Antenna Type	Omni-directional
Simulation time	1000 sec

4.6. Effect of Network Density

Results and analysis of AODV and DSR with varying number of nodes have been presented in the following section.

4.6.1. Packet Delivery Ratio

The PDR shown in Figure 4.3-a reveals that AODV generally shows better performance than DSR with both mobility models. The performance of AODV and DSR is better with random waypoint with attraction points. DSR with RWP mobility pattern is poor for all numbers of nodes, but especially for more than 75 nodes.

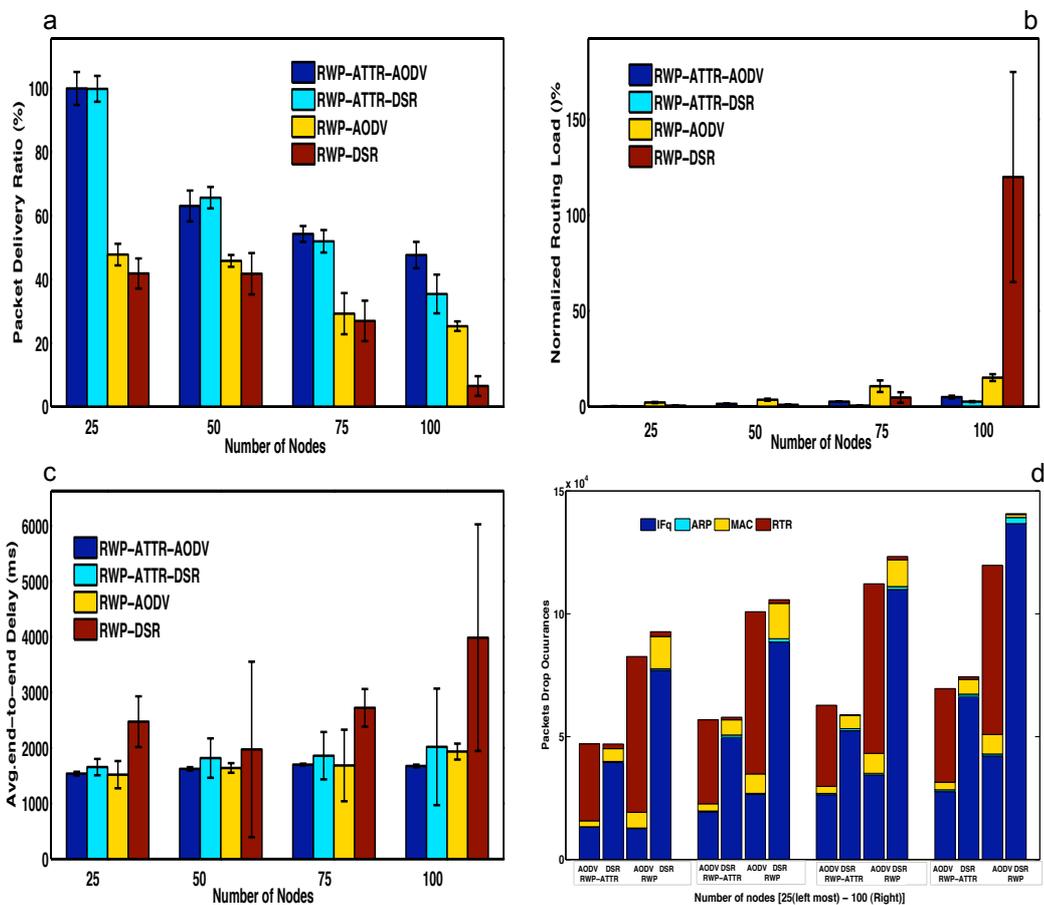


Figure 4.3: a) PDR vs Number of Nodes
 b) NRL vs Number of Nodes
 c) Mean Delay vs Number of Nodes
 d) Dropped Packets vs Number of Nodes

4.6.2. Normalized Routing Load

We observe that DSR under conditions of RWP mobility exhibits enormous performance degradation in terms of routing load with higher node density (Figure 4.3-b & Figure 4.4).

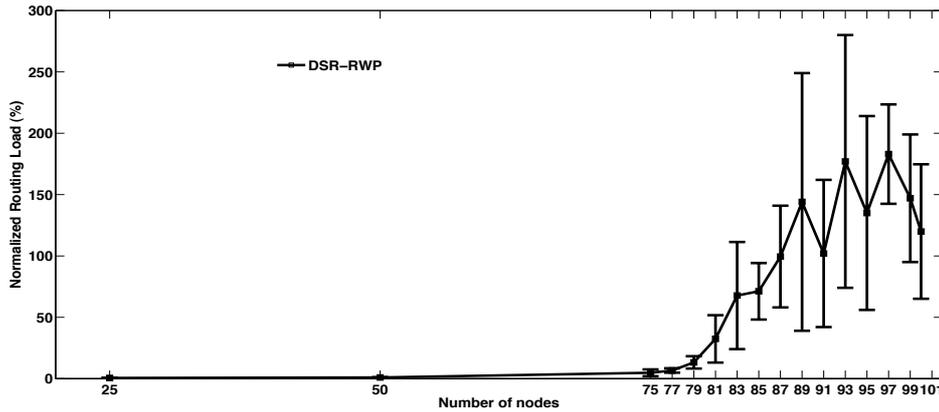


Figure 4.4: NRL vs Number of nodes

For 100 nodes, the normalized routing load is 119 with RWP-DSR and is just 15 with RWP-AODV. A separate simulation run with RWP mobility for DSR protocol was conducted reducing the step size to two nodes after 75 nodes (see Figure 4.4). It was found that DSR performance gets specifically poor with sharp increase in NRL. For 75 nodes, the NRL for RWP-AODV and RWP-DSR is 10.67 and 4.77 respectively (see Figure 4.3-b). The performance of DSR degrades rapidly with increasing number of nodes (Figure 4.4). Again, performance is better with RWP-ATTR mobility pattern for both AODV and DSR. Increasing node density increases the neighbour count $\left[\pi \times r^2 / \frac{w \times l}{n} \right]$ [Kurkowski05] and this may increase the probability of collision which, in turn, leads to more retransmission attempts, and thus increases the routing load significantly. As seen in Figure 4.3-d, more packets are dropped in case of DSR (DSR uses its full cache before initiating new RREQ) as IFq is full where as lack of available route is the major cause of packets drop in AODV (only route per destination is available in AODV). In case of RWP with AODV, routing load increases from 2 to 15 when the number of nodes increases from 25 to 100. The generally poor performance with using DSR for RWP may be explained by the aggressive route caching technique built in this

protocol, but for a higher node density, the benefit of caching routes seems to be lost.

4.6.3. Mean End-to-End Delay

We observe that Mean Delay (Figure 4.3-c) increases relatively slowly with increase in number of nodes for AODV and DSR in RWP-ATTR mobility pattern, but DSR with RWP shows a strong rise in delay as the number of nodes increases from 50 to 100. This is due to large overhead packets (i.e. complete route information in packet header) in DSR as compared with AODV. Higher node density increases the number of neighbouring nodes and that causes more route reply messages to the source node and thus increases delay.

4.7. Network Performance with varying mobility

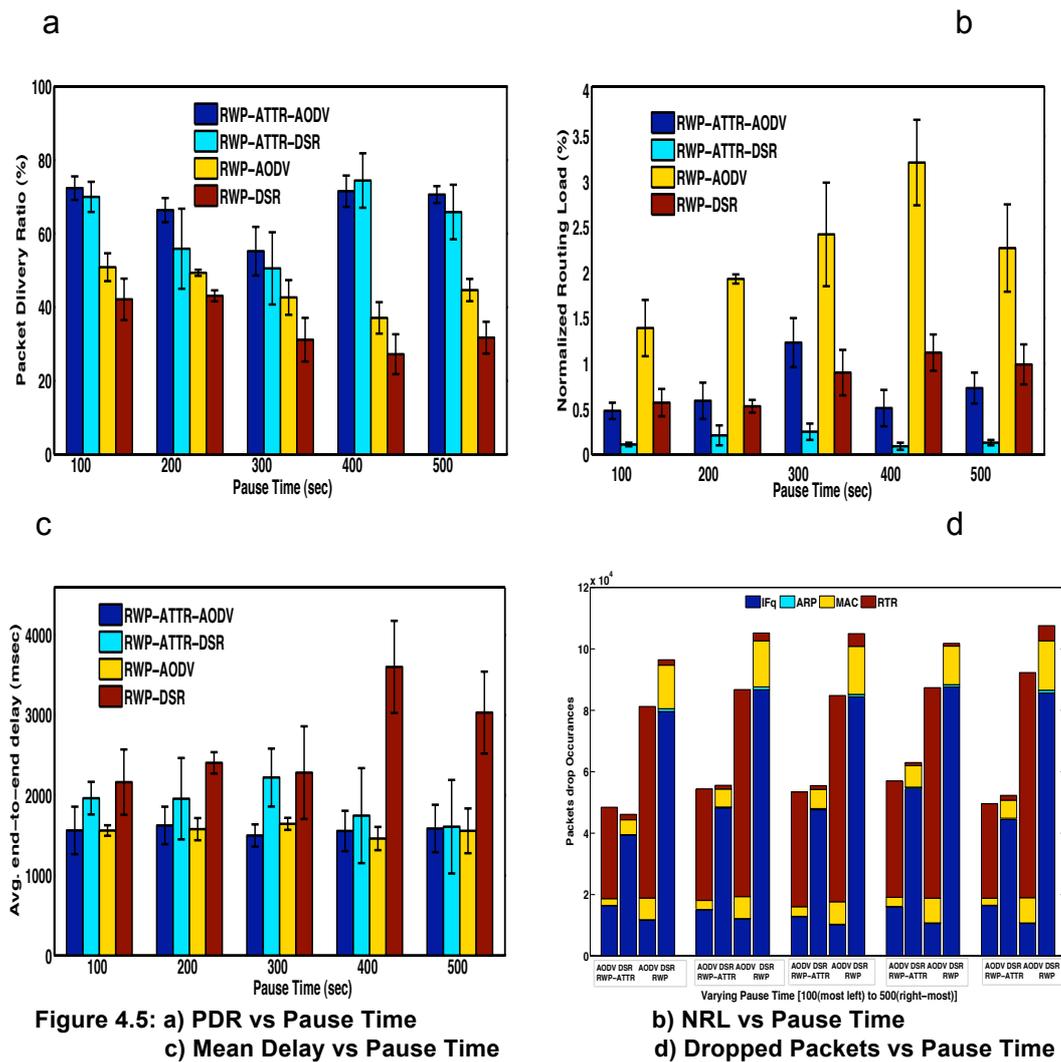
The simulation parameters employed in simulations studying the effect of varying the mobility level (lower pause time means higher mobility and vice versa) are shown in Table 4.3.

Table 4.3: Simulation parameters with varying pause time

Parameter	Value
Protocols	AODV, DSR
No. of nodes	25
Area size	500x500 m ²
Max. Speed	1 m s ⁻¹
Mobility Models	RWP, RWP (ATTR)
Traffic Type	CBR
Packet size	512 bytes
Rate	8 pkts sec ⁻¹
Queue Length	50
Pause time	100,200,300,400,500 (sec)
No. of traffic sources	20
Transmission range (r)	250 m
Radio channel frequency	2.4 GHz
Propagation path loss model	Two ray ground
Antenna Type	Omni-directional
Simulation time	1000 sec

4.7.1. Packet Delivery Ratio

Comparing the routing protocol performance with increasing pause time (Figure 4.5-a), AODV and DSR show significantly better results if the mobility behaves like RWP-ATTR pattern. The behaviour of non-uniform node distribution with RWP affects protocol performance significantly because the nodes tend to cluster in the centre of the simulation area.



4.7.2. Normalized Routing Load

From Figure 4.5-b, it can be readily observed that DSR has the lowest routing overheads with RWP-ATTR and AODV shows higher overheads with RWP

varying from a minimum load of 1.4% to a maximum load of 3.2% as the pause time increases to 400s. DSR shows overall better performance than AODV with varying pause time with both RWP and RWP-ATTR mobility models. Routing overheads in DSR consist mainly of RREP messages whereas RREQ messages constitute the main fraction of routing load in AODV. New route discovery is less frequent in the case of DSR because of the caching technique employed, as there is mostly some valid route available in DSR whereas AODV has at most one route available per destination. By use of aggressive caching, DSR protocol usually find routes from cache source and hence exhibits less routing load. Again, the major cause of packet drops is 'full IFq' and 'no route' for DSR and AODV protocol respectively under both mobility models (Figure 4.5-d).

4.7.3. Mean End-to-End Delay

We observe that AODV shows lower delays than DSR (see Figure 4.5-c) for both mobility types. This again results from the large packet header used in DSR, which causes delays, and also where stale routes are held for a long time, delays occur in establishing connections.

4.8. Impact of Leader's mobility behaviour in RPGM model on MANETS

The RPGM model [Hong99] seems to be a suitable model to mimic mobility behaviour typically found in disaster area relief scenario or military regimental movements in battlefields. In this model, nodes tend to move in cluster formations with group heads (known as group leaders) while follower nodes just pursue the cluster head motion. This study investigates four different types of random mobility models (for group leaders) and

analyses its influence on the performance of DSR in MANETS. The effects of Levy-Walk, Probabilistic Random (Prob-Rand), Random Direction (Rand-Dir) and Random Walk (Rand-Walk) leader mobility models were observed for varying communication load and transmission range.

Using *ns-2.34*, we have analyzed the performance of MANETS with varying communication load from a normal load of 8 sources to a stressed environment with 24 sources (20 pkts/sec) and changing the node transmission range from 50 m to 250 m. Three network performance metrics (i.e. Packet Delivery Ratio (PDR), Routing Overheads (i.e. total count of routing packets) and Mean end-to-end delay) were considered. This study is not the first and definitely not the last one that has used RPGM model for MANETS performance analysis e.g. [Jayakumar08], [Alshanyour10], [Davies00],[Harminder10]. However, as far as we know, all of the reported studies have used the Random Waypoint mobility model for leader's mobility and have not introduced any other mobility models.

The topography showing the node movement patterns for RPGM model with four variations of cluster head motions used in our simulation is presented in Fig.4.6. It is evident that with Levy-Walk and Prob-Rand mobility behaviour, nodes tend to stay closely within group domain whereas with Rand-Dir pattern, groups move until they meet the boundary of the simulation field and may experience less connectivity. Figure 4.6-right shows the complete footprints of group movements for an example 500 sec simulation time. With Levy Walk pattern, nodes mainly move in the centre and around of the network field and by virtue of this behaviour, nodes may enjoy better link quality and duration. Whereas with Prob- Rand

movements, group movement is constrained in relatively smaller areas of the whole simulation field. With Rand-dir and Rand-Walk movements, nodes take longer walking trips covering almost majority of the whole area and this behaviour can have considerable impact on connectivity between different groups.

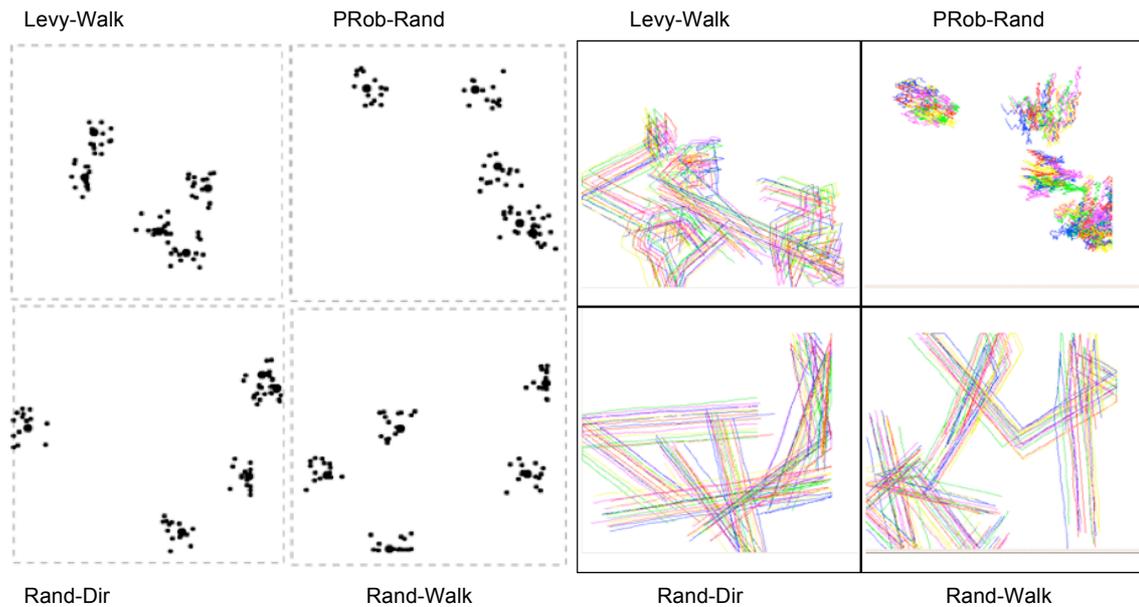


Figure 4.6: Left: Snapshots of mobility patterns used in our simulations capture during the middle of an example 500 secs simulation run and footprints of node movements (Right).

4.9. Research background & methodology

The main aim of this study was to investigate the impact of group leader's mobility patterns on routing performance in MANETS with varying communication load and transmission ranges. Mobility files were generated for different mobility patterns in a fixed area of 1000 X 1000 metres. Mobile nodes were initially distributed randomly on the simulation field with boundary reflection attribute (i.e. nodes will stay in the simulation area during the whole simulation period). A cutoff period of 1000 secs was used to stabilize mobility behaviour of nodes. We generated five mobility files for

each mobility scenario. Each result is an average of five simulation runs with identical input parameters but with a different random seed. We used IEEE 802.11b equipped radios with Omni directional antennas (height of 1.5 m) and a receiver threshold of -84.5 dBm at 2 Mbits/s data rate. Standard CMUPri model (for queue) with buffer size of 50 was used. Two Ray Ground was used as the radio propagation model taking into consideration both the direct and indirect paths. Again considering the argument of Chapter 2, this propagation model may not give realistic results in heavily builtup areas. Some key simulation parameters for both scenarios are shown in Table 4.4.

Table 4.4: Simulation parameters with varying traffic load and Transmission ranges

Parameter	Value
Simulation time	500 secs
Area size	1000x1000 m
Mean speed	1.5 m sec ⁻¹
Traffic type	CBR
Packet size	512 bytes
No. Of Max. Traffic sources (Max. CBR Connections scenario)	8,12,16,20,24
No. of Max. Traffic sources (Transmission range scenario)	8
Rate	20 pkts/sec
Channel frequency	2412 MHz
Mobility model	Reference point group mobility
No. of nodes	75 (divided in 5 groups)
Leaders mobility patterns	Levy Walk, Prob-Rand, Rand-Dir, Rand-Walk
SDR and ADR	0.05
Max. Initial distance	50meters
Pause time	0 sec
Transmitter power (Max. CBR Connections scenario)	7 dBm
Transmitter power (Transmission Range scenario)	-10.9, -4.9, -1.4, 1.1, 3 (dBm)
Tx and Tr antenna Gain (Gt=Gr)	1
Received power threshold (RXThreshold)	-84.5 dBm
Carrier sense threshold (CSThreshold)	-84.5 dBm

4.10. Results Discussion

Results and analysis for DSR protocol with varying traffic sources and transmission ranges are presented in the following sections.

4.10.1. Packet Delivery Ratio

The effect of varying the communication load from 8 sources to 24 sources with various mobility behaviours taken by group leaders in MANETS is presented in Figure 4.7-left. It is evident that Levy-Walk mobility pattern leads to the best performance. Generally, the worst performance occurs when the mobility behaves like Random-directional model. This is because the nodes move up until the boundary of network field (see Figure 2.10 & 4.6) for each movement they make and hence the range between groups may be longer than the transmission range. Comparing the protocol performance with increasing transmission range, it is apparent that (Figure 4.7-right) DSR performs well with Levy-Walk model with increasing transmission range. Again, performance of DSR is moderately low if group head's mobility behaves like Rand-Dir and Rand-Walk model. In a sparsely connected network (i.e. low transmission range), there are more chances of link breaks which results in lower PDR. Increasing transmission range certainly increases network performance with all models as more nodes are in the neighbourhood of each other.

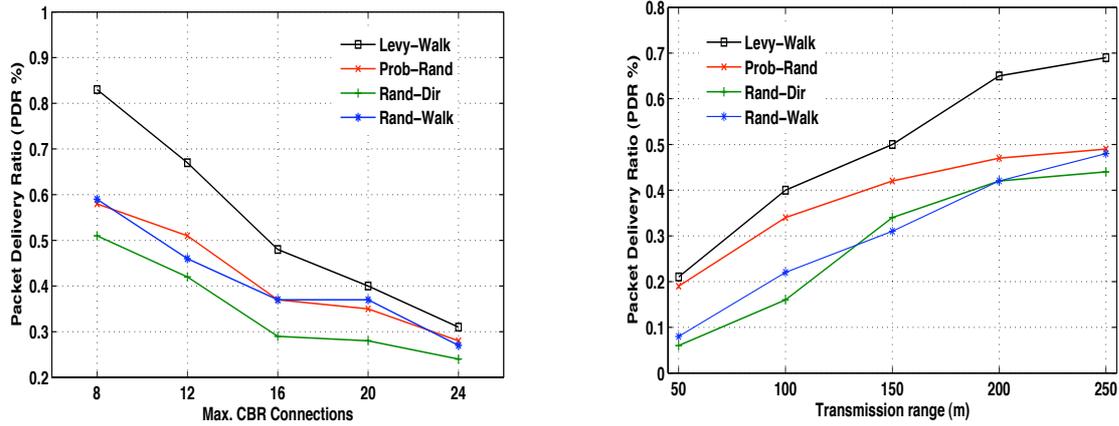


Figure 4.7: (Left) PDR vs Max. CBR Connections, (RIGHT) PDR vs Transmission Range

Max. CBR Connections	Levy-Walk	Prob-Rand	Rand-Dir	Rand-Walk	Transmission Range	Levy-Walk	Prob-Rand	Rand-Dir	Rand-Walk
8	0.14	0.18	0.07	0.1	50	0.16	0.13	0.018	0.04
12	0.12	0.18	0.012	0.11	100	0.22	0.16	0.014	0.07
16	0.1	0.11	0.03	0.07	150	0.19	0.15	0.058	0.08
20	0.07	0.12	0.03	0.05	200	0.18	0.16	0.06	0.12
24	0.04	0.09	0.04	0.02	250	0.15	0.19	0.04	0.12

Table 4.5: STD for DSR-Max. CBR Connections and DSR-Transmission Range PDR results

4.10.2. Routing Load

We observe that the routing overheads (i.e. count of total routing packets) go notably high (see Figure 4.8-left) with Rand-Dir and Prob-Rand mobility models for DSR. The network experiences low routing load with increasing network traffic for Levy-Walk mobility model. Low routing overhead is critical in MANETS with nodes equipped with limited battery power and transmission capabilities. Increasing routing packets can significantly impair the network performance. Increasing the transmission range generally increase routing overheads (see Figure 4.8-right) for DSR in MANETS. This is understandable as increasing transmission range means an increase in PDR which leads to more routing overheads. Also with the broadcast nature for new route

discovery in DSR, the routing load gets higher with increasing neighbour count.

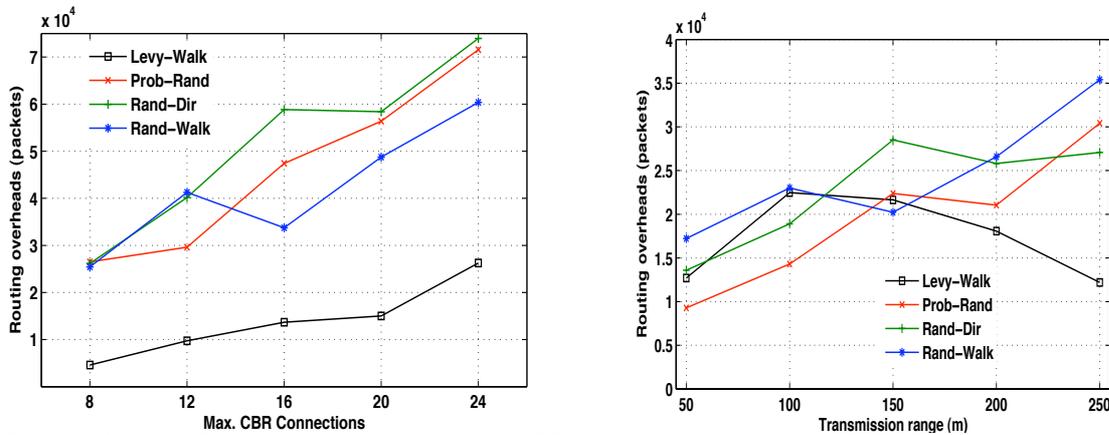


Figure 4.8: (Left) Routing overheads vs Max. CBR Connections, (RIGHT) Routing overheads vs Transmission Range

Max. CBR Connections	Levy-Walk	Prob-Rand	Rand-Dir	Rand-Walk	Transmission Range	Levy-Walk	Prob-Rand	Rand-Dir	Rand-Walk
8	4370	24800	18100	5260	50	11700	2620	5710	14800
12	10900	30300	19600	26600	100	8780	7980	13100	19200
16	12200	31400	9600	31500	150	12900	11000	15000	9330
20	26200	41300	25700	33600	200	18200	11900	9580	10400
24	25700	46500	22400	21600	250	10700	24600	13000	18000

Table 4.6: STD for DSR-Max. CBR Connections and DSR-Transmission Range routing overheads results

4.10.3. Mean end-to-end Delay

It can be readily observed that the delay generally increases linearly with increasing network load for all mobility models (see Figure 4.9-left). DSR experiences higher delay with Levy-Walk model than with other mobility models mainly because more packets are delivered (higher PDR than others). We observe that DSR shows relatively high end-to-end delay (Figure 4.9-right) with Rand-Dir mobility pattern for increasing transmission range. Increasing transmission range increases delay with all scenarios for DSR except with Levy-Walk mobility model. This unusual behaviour may have

been caused due to nodes having good neighbourhood which can reduce the hop count and hence the Mean Delay.

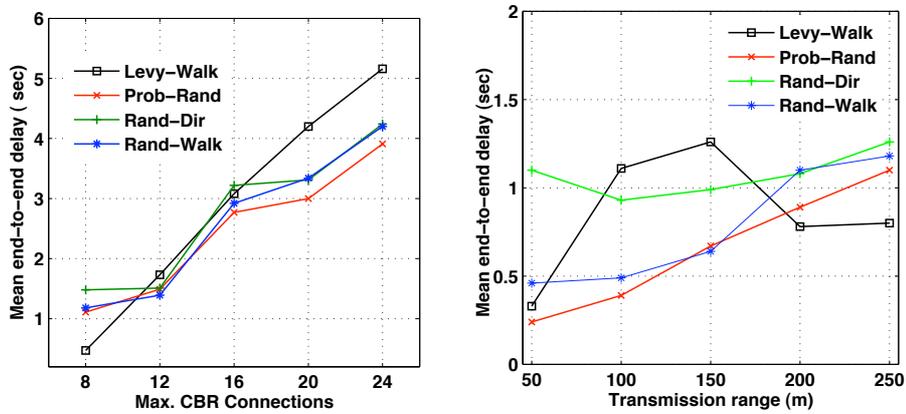


Figure 4.9: (Left) Mean Delay vs Max. CBR Connections, (RIGHT) Mean Delay vs Transmission Range

Max. CBR Connections	Levy-Walk	Prob-Rand	Rand-Dir	Rand-Walk	Transmission Range	Levy-Walk	Prob-Rand	Rand-Dir	Rand-Walk
8	0.4	0.57	0.52	0.39	50	0.43	0.41	1.31	0.71
12	0.2	0.32	0.87	0.27	100	0.6	0.34	1.006	0.44
16	0.29	0.87	0.94	0.37	150	0.42	0.51	0.88	0.26
20	0.29	0.76	0.86	0.58	200	0.33	0.58	1.22	0.76
24	0.82	0.92	1.14	0.62	250	0.25	0.6	0.73	0.47

Table 4.7:STD for DSR-Max. CBR Connections and DSR-Transmission Range Mead Delay results

4.11. Summary

This chapter presented the performance analysis of two MANETS routing protocols. In the first part of this Chapter, we have examined the impact of two mobility models, random waypoint and random waypoint with attractions on the performance of two on demand routing protocols. It has been observed that the mobility behaviour of the nodes has a strong influence on the performance of MANET routing protocols. The number of Link Breaks and the Avg. Link Duration are dependent upon the mobility behaviour of nodes and have a significant impact on network performance. Nodes suffer with higher

link breaks and low connectivity (i.e. Avg. link duration) if the mobility behaves like RWP pattern. Alongside we observe that performance of DSR is significantly poorer as node density increases. Compared to RWP-ATTR, which is immune from non-uniformity of node distribution, RWP mobility has negative effects on both AODV and DSR. DSR exhibits severe degradation in performance with higher node density, which leaves a question mark on its ability to perform in stressed circumstances. In high node density environments, AODV appears to be a better protocol choice than DSR for stressful MANET environment (i.e. higher network size & mobility levels). Depending upon the mobility constraints and network size, the following observations have been concluded.

- Network suffers with performance degradation with increasing node density more severely if the mobility behaves like RWP pattern. As node density increases, mobility induced occurrence of link breaks increases significantly, which affects the routing protocol performance negatively.

- Network running with AODV sends data packets carrying the destination address only, however DSR requires data packets to carry the complete source-destination route, which increases the DSR network overheads. Due to this fact, a network running with AODV occupies less bandwidth than with DSR. On the other hand, AODV broadcasts periodic HELLO messages and sends more control messages than DSR. However when the network size increases (i.e. 75 nodes), DSR suffers from a sharp decline in the performance metrics. An increase in network size also increases the number of link breaks and hence results in more frequent route errors. RERRs are handled differently in AODV and DSR (i.e. unicast in DSR and broadcast in

AODV) which results in more routing overheads in DSR. DSR uses aggressive caching technique, which is useful when the network size is small, however DSR does not have any specific mechanism to delete stale routes in route cache which affects its performance adversely as the network size gets larger (i.e. in terms of node density).

- In a low density environment (i.e. low number of nodes), DSR performs better than AODV for NRL metric under both mobility models (see Figure 4.5-b).

The second part of this chapter has studied the effects of a group mobility model (i.e. RPGM) on MANET performance for the DSR protocol with varying traffic load and transmission ranges. The RPGM model has been adopted in MANET research community to mimic group mobility where nodes move in group formations following their respective group heads. However, the mobility behaviour adopted by group heads influences the overall mobility and hence the MANET performance. Four variants of group head's mobility model (i.e. Levy-Walk, Prob-Rand, Rand-Dir and Rand-Walk) were tested and their influence was examined for DSR protocol. It was concluded that

- Mobility behaviour adopted by group leaders in RPGM model significantly influences the overall mobility pattern and hence the network performance in MANETS.

- The network performance improves considerably if the leader's movement is either the Levy-Walk or Prob-Rand type of mobility.

Chapter 5

Scalability in MANETS

5.1. Introduction

Recent advances in the size, power and hardware resources of wireless devices have resulted in proliferation of these devices. As the number of users continues to grow, scalable routing protocols will be in demand to facilitate the large population of nodes. Furthermore the widespread use of wireless devices and development of new applications for wireless networks will lead to the development of large adhoc networks. For example, in a conference room MANET scenario, there may be hundreds of participants joining the same adhoc network and hence nodes must be capable of configuring and establishing routes. There have been many unicast protocols that have been developed in this context such as AODV and DSR. Other approaches like clustering and hierarchical addressing have also been developed to enhance the scalability of routing protocols in MANETS [Lee03]. However, the majority if not all the published work in MANET routing scalability have either ignored or have used simplified physical layer modelling. For example, Lee *et al* [Lee03] have discussed the issue of scalability of AODV and simulation results have been presented for up to 10,000 nodes in a Free Space propagation environment using GlomoSim simulator. GlomoSim [Zeng98] is a scalable simulation environment for wireless networks that uses parallel discrete-event simulation capability. However the authors do not address the critical analysis of propagation layer in this context. Kuan *et al* [Kuan06] cover the simulation results for AODV and

DSDV protocols for up to 200 nodes and using Free Space propagation model that may reduce the effect of packet collisions but may not be very realistic in urban mobile scenarios. There is still a need to look upon the scalability issues in a more realistic propagation environment. The scope of this chapter is to address this issue by analysing the MANET performance under ITU propagation models for urban environment.

There have been various studies conducted considering the scalability issues in wireless networks. Hamida *et al* [Hamida09] describes the importance of PHY layer and scalability issue (using their proprietary simulator *WSnet*) for static wireless sensor networks using up to 1500 nodes. Valery and Thomas [Valery05] describe the techniques to enhance the scalability for AODV and DSR protocols and present the simulation results for up to 550 nodes using *ns-2*. However, the propagation model used for simulation analysis has not been described. David [David03] simulates AODV for 1000 nodes using Qualnet simulator and the PDR for 1000 nodes remains above 90%. However, the simulation analysis carried out in this chapter only gets a PDR of 96% using 200 nodes with TRG propagation model. Increasing nodes (i.e. up to 1000) drops PDR to just 15% (8 traffic sources), which is not even worth to configure a reliable network. The performance degrades even further if the channel behaves like the ITU-R models. This huge difference makes important to analyze the MANET scalability in presence of a realistic wireless propagation scenario. This chapter covers the performance of AODV with varying node density (i.e. increasing the number of nodes in two fixed areas) and scalability by increasing the terrain size but for same node density.

5.2. Simulation & Mobility Environment

ns-2 simulator has been used for all analysis. MG mobility model was used for two rectangular areas (i.e. 1000x1500 m & 2000x3000 m terrain sizes). MG mobility model was selected in order to have more scattered movement of nodes and to mimic a typical street movement scenario. As nodes move in restricted lanes under this mobility model and have less connectivity (see Figure 3.3) compared with other random motion models. This model can mimic more realistic mobility and propagation conditions (i.e. considering corner loss scenarios) for urban areas MANETS analysis. All blocks were equally apart in both terrain sizes (i.e. 75 meters gap between lanes). The simulation analysis was carried out by changing the number of nodes but keeping the node density same in both simulation environments. Each result is an average of five simulation runs. Table 5.1 summarizes the terrain sizes and No. of nodes in each scenario. The No. of nodes under 2000x3000 m

Table 5.1: Summary of node density and terrain sizes

Terrain Size and No. of Nodes		Average Neighbourhood
1000x1500 m	2000x3000 m	
50	200	6.54
100	400	13.08
150	600	19.63
200	800	26.17
250	1000	32.72

terrain size were increased as to keep the average connectivity (neighbourhood) among nodes common for both terrains. The purpose of this study is two fold; one is to analyze the effect of node density under same

terrain size and second is to analyze the impact of scalability by increasing the terrain size and network traffic but keeping the node density common for both scenarios. The simulation tests have been conducted in a challenging environment with zero pause time and varying random traffic sources from 4 to 8. Some of the common simulation parameters are described in Table 5.2.

Table 5.2: Simulation Parameters with different terrain sizes

Parameter	Value
Simulation time	500 secs
Area size	1000x1500 m & 2000x3000 m
Mean speed	1.5 m sec ⁻¹
Traffic type	CBR
Packet size	512 bytes
Connection rate	8 pkts sec ⁻¹
No. of Traffic Sources	4 & 8
Propagation Models	ITU-LoS&NLoS
	TRG
Transmitter power	8.6 dBm
Tx and Tr antenna Gain (Gt=Gr)	1
Received power threshold (RXThreshold)	-84.5 dBm
Carrier sense threshold (CSThreshold)	-84.5 dBm

5.3. Results & Discussion

This section covers the discussion about produces results. The analysis is done for the performance metrics such as PDR, NRL and No. of packet collisions, which is the total number of packets, dropped due to collisions at the MAC layer (considering the impact of physical layer).

5.3.1. Packet Delivery Ratio

Figure 5.1 shows the effect of node density, scalability and traffic load on the performance of AODV under TRG and ITU models. It is evident that node density and scalability affects adversely the network performance for AODV under ITU and TRG models. However the effect of ITU on the performance of AODV is more significant than TRG. Network suffers with significantly lower

PDR if the channel behaves like ITU propagation model. As more nodes get into neighbourhood of each other, this causes congestion and decreases the PDR considerably. Generally, as the network area grows, there are more longer communication paths experienced by nodes which results in more link breaks and eventually degrades the performance.

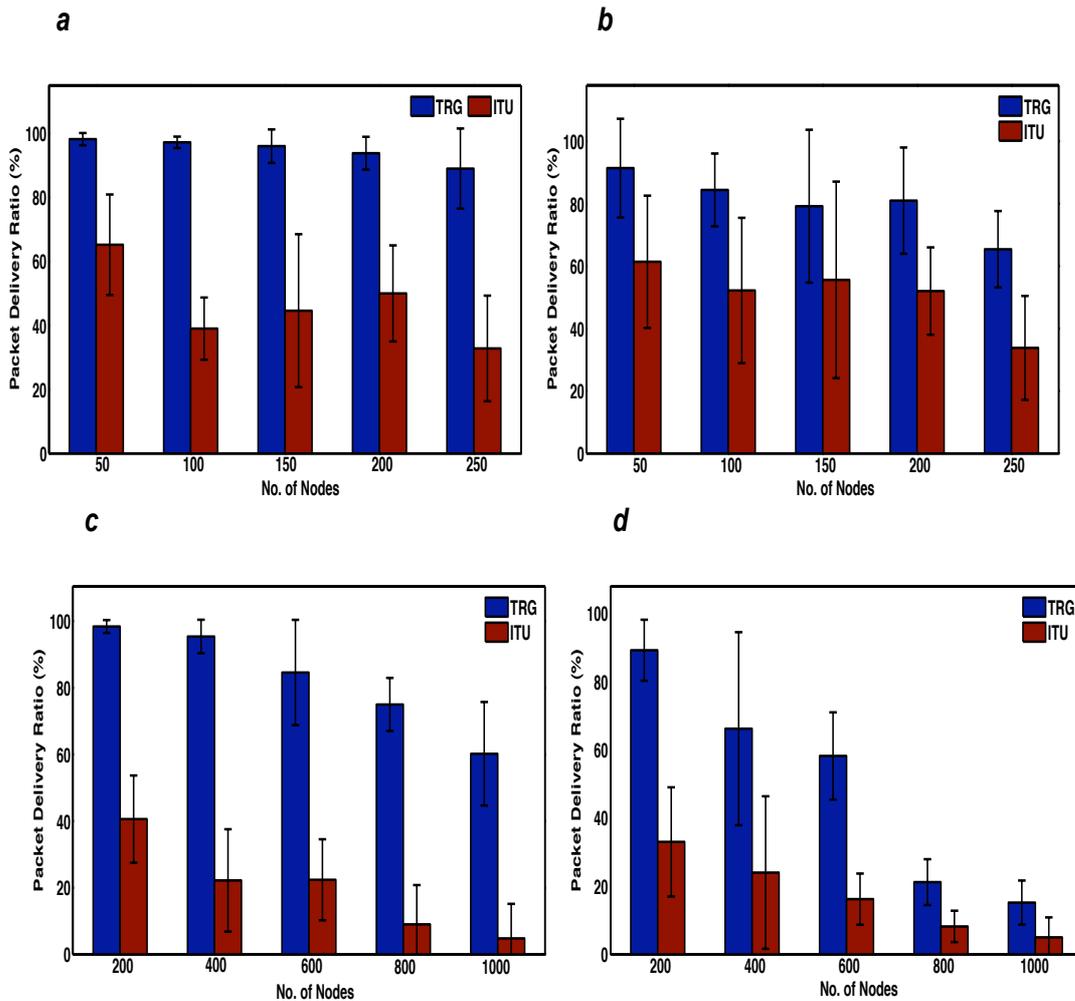


Figure 5.1: PDR vs No. of Nodes for
a) Terrain size: 1000x1500 ; Traffic Sources: 4
b) Terrain size: 1000x1500 ; Traffic Sources: 8
c) Terrain size: 2000x3000 ; Traffic Sources: 4
d) Terrain size: 2000x3000 ; Traffic Sources: 8

5.3.2. Normalized Routing Load

NRL is the most important performance parameter with regard to network scalability. The routing load evaluates the internal efficiency of a routing

protocol. Higher routing load will lead to more power and bandwidth consumption in a resource constrained environment. A higher routing load will also cause congestion leading to packet collisions in large adhoc networks. Figure 5.2 shows the NRL for changing node density, scalability and traffic load effects for AODV. It is apparent that network suffers with extremely high NRL if the wireless channel conditions are like ITU propagation model. Also there is higher fluctuation (i.e. high std. deviation) observed in network performance with ITU model. With 10 dB capture threshold value (default SIR ratio in *ns-2*), it is clear that increasing node density and scale increases NRL significantly. Due to mobility and poor channel conditions experienced by nodes in ITU model, there are more link breaks among nodes, which leads to more RREQ attempts by nodes during simulation. As RREQ messages are broadcasted which causes flooding in the network and hence increases the routing load significantly. The impact of flooding is limited in a relatively small network (i.e. few tens of nodes). However as the network size grows it influences the routing load drastically. On the other hand, as the terrain size increases, there are longer communication paths between nodes, which also affect the NRL significantly. In an urban area, the presence of obstacles and objects causes multipaths, which results in higher fluctuation in received signal strength and leads to frequent RREQs. Reducing the NRL is still a challenge for larger MANETS as higher routing load results in lower PDR and higher Mean Delay. Comparing equal node density effect with reference to area (i.e. 50 nodes to 200 nodes & 250 to 1000 nodes), there is a much higher increase in NRL with ITU model than with TRG model. However the increase in ratio is 61 & 160 (for 4 traffic sources, see Figure 5.2-a & c) and

95 & 52 (for 8 traffic source, see Figure 5.2-b & d) with TRG and ITU models respectively. It can be said that the effect of node density (with higher traffic) is more severe with TRG model than with ITU model. Also, the effect of scalability is more significant on the performance of AODV with ITU model. In a smaller network, AODV performs well with higher PDR and lower NRL if the channel is like TRG model. As simulation environment get stressed (i.e. caused by increase in number of nodes, network traffic, mobility trace or poor channel conditions), the simulation results show higher fluctuations.

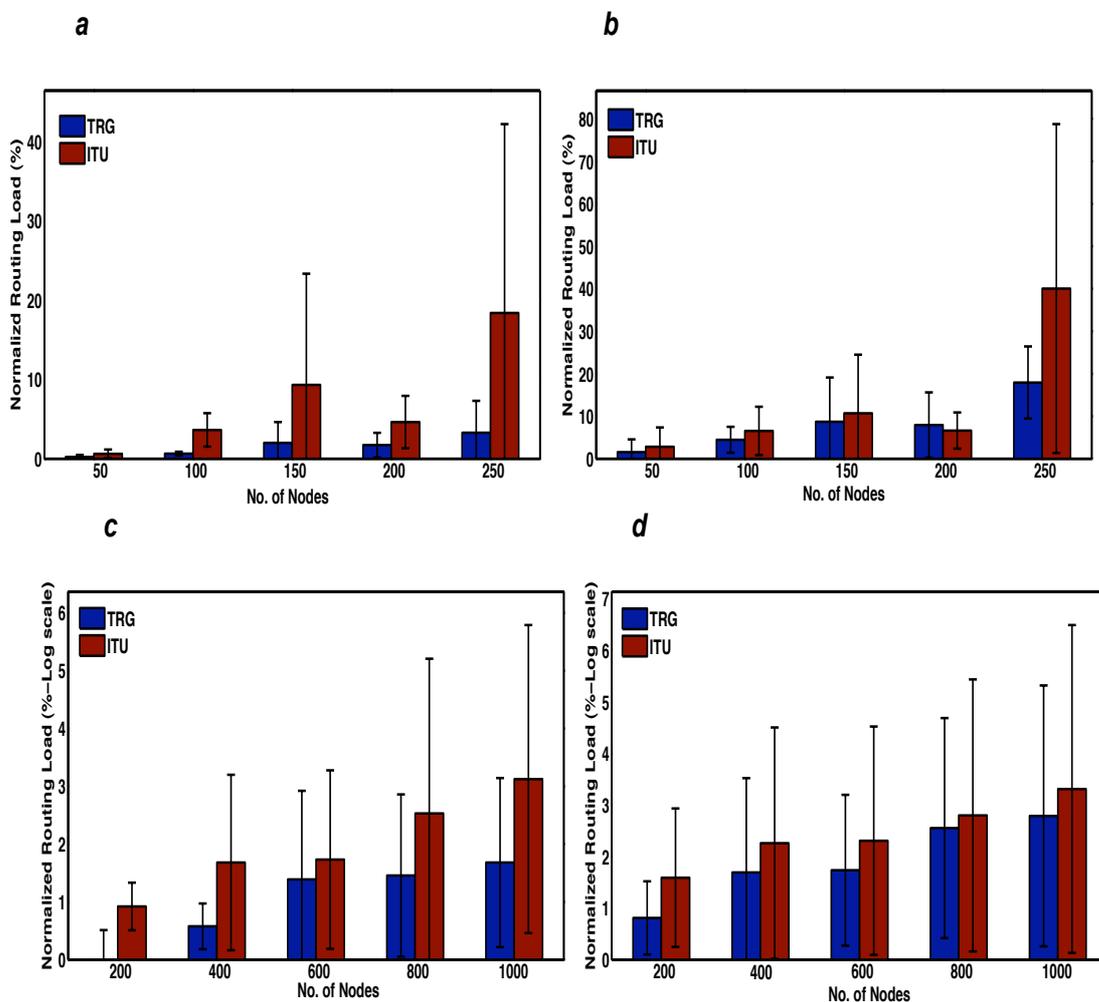


Figure 5.2: NRL vs No. of Nodes for
a) Terrain size: 1000x1500 ;Traffic Sources: 4
c) Terrain size: 2000x3000 ;Traffic Sources: 4

b) Terrain size: 1000x1500 ;Traffic Sources: 8
d) Terrain size: 2000x3000 ;Traffic Sources: 8

5.3.3. Packet Collisions

Figure 5.3 shows the occurrence of packet collisions with increasing node density, network and traffic size. Collision occurs when two or more nodes within neighbourhood of each other try to transmit at the same time. It can be said that the probability of packet collision increases with the number of nodes in the same area. More nodes will try to send which increases the coinciding simultaneous transmissions and hence the No. of packet collisions.

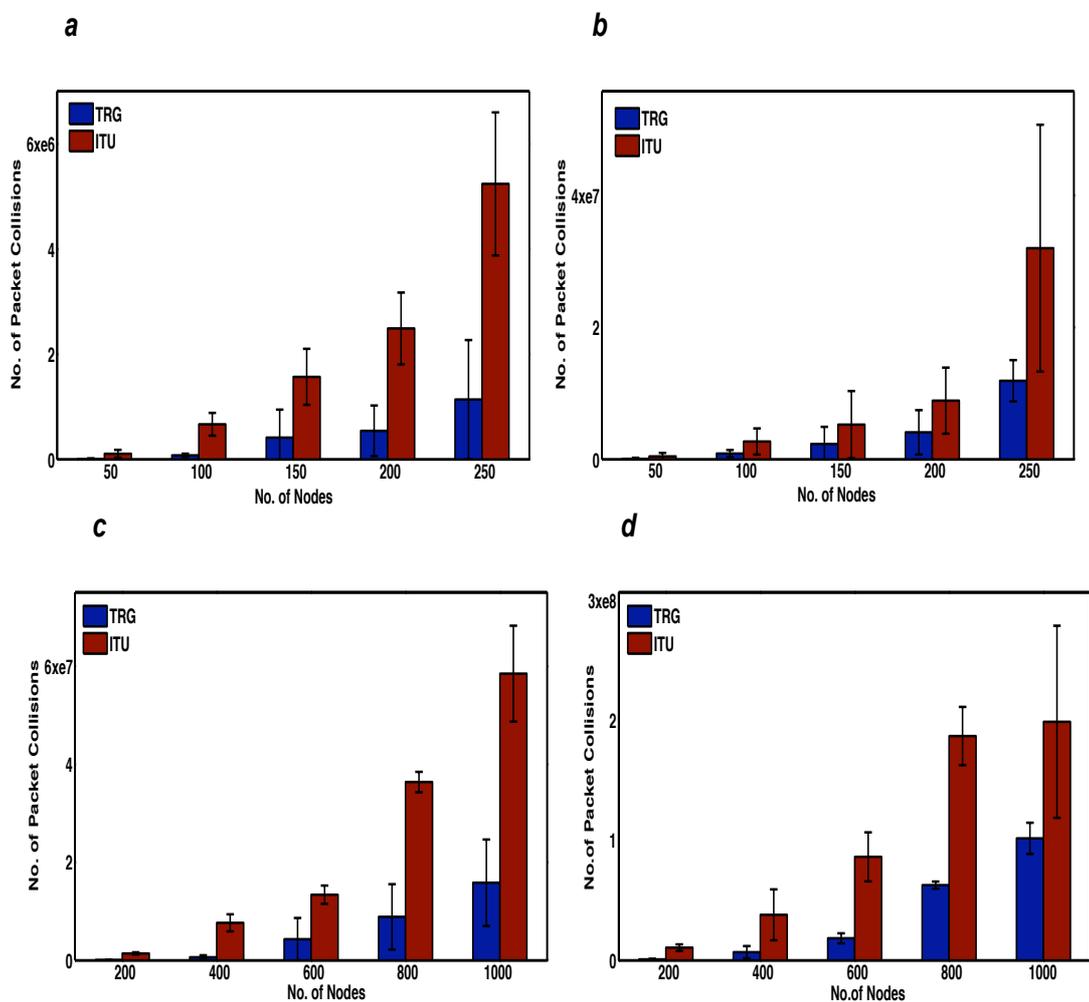


Figure 5.3: Packet collisions vs No. of Nodes for
a) Terrain size: 1000x1500 ; Traffic Sources: 4
c) Terrain size: 2000x3000 ; Traffic Sources: 4

b) Terrain size: 1000x1500 ; Traffic Sources: 8
d) Terrain size: 2000x3000 ; Traffic Sources: 8

Fewer nodes in the same area results in less probability of collisions. Also with poor channel conditions, there are more retransmission attempts that leads to congestion and hence increases packet collisions. It is evident from the results that the network experiences many more packet collisions with the ITU-R model for AODV, because with the ITU-R model, there are more RREQs generated (i.e. higher routing load see Figure 5.2) which results in more broadcast packets and hence increases the No. of packet collisions. Increasing network size on a bigger terrain also increases the collision occurrences significantly in the presence of weaker propagation condition.

5.4. Summary

This chapter covers the analysis of AODV in scalable environment with the effect of ITU-R propagation models. Many reported studies about routing scalability neglect the physical layer and use simplistic models such as the Free Space model. However using a more realistic propagation model has a significant impact on AODV performance. By simulation results, it has been observed that the network performance declines sharply with increase in node density and network size if the channel conditions are poor. MG mobility model was used for all simulation analysis in order to analyze the LoS and NLoS propagation impact on AODV routing performance. The effect of terrain size is more significant with TRG than with ITU propagation models on AODV performance. With increasing AODV scalability, the degree of change in routing load is 3 to 4 times higher if the wireless channel behaves like TRG model. In order to have confidence in simulation results, this study shows that the correct modelling of PHY layer in MANET simulation environment is crucial.

Chapter 6

Indoor Performance of MANETS

6.1. Introduction

MANETS have been proposed for emergency relief scenarios (i.e. such as fire, paramedics, police and military), which may occur in indoor/outdoor environment. Hence, it is important that MANET protocols should be simulated in both the indoor & outdoor environment with appropriate propagation modelling. Chapters 3, 4 and 5 have evaluated the outdoor scenarios with propagation models considered accordingly. This chapter analyses MANET performance in the indoor environment considering relatively small number of nodes. An *ns-2* based simulation of the AODV and OLSR protocols with varying propagation models such as ITU-R (i.e. mentioned in Section 2.6.5) and WINNER [Kyosti07] (Wireless world INitiative NEw Radio) considering indoor pathloss environment is considered in the first part of this chapter. The second part of this chapter compares the observations from a 3-node testbed with those produced through simulation for the AODV-UU protocol.

6.2. Simulation based AODV & OLSR Performance Comparison

The work done in this section evaluates the strength of two routing protocols (considering OLSR (a proactive) and AODV (a reactive) protocol) under the influence of ITU and WINNER propagation environments. WINNER was developed by a consortium of five organizations (Nokia, OULU university,

Communication Research Centre Canada, Technische Universitat Ilmenau & Elektrobot EBITG). This model was developed based upon measurements on a university campus [Kyosti07]. The generic WINNER channel model follows a geometry based stochastic channel modeling approach, which allows an arbitrary double directional radio channel to be created. The path loss for an indoor non line of sight (NLOS) case can be described as

$$P_l = 36.8 \log_{10}(d[m]) + 43.8 + 20 \log_{10}(f[\text{GHz}/5.0]) \dots \dots \dots (6.1)$$

Where d is the separation distance between T_x and R_x and f is the operating frequency.

6.3 Literature Survey

There have been very few studies that have simulated MANET routing performance in the indoor environment. However, there has been relatively large number of published literature available where indoor MANET performance has been analysed based upon testbed results. By way of contrast for outdoor MANET scenarios, the weighting of the literature between simulation and experiment is the other way round. This is mainly because it is relatively easy to implement testbeds indoors than outdoors and it is difficult to justify indoor simulation based analysis with the simplistic mobility and propagation models typically found in available simulators. Cavilla *et al* [Cavilla04] have analysed indoor MANETS with various constrained mobility models and with Attenuation Factor [Rappaport96] propagation environment.

Dricot *et al* [Dricot03] have analysed the performance of various routing protocols using Shadowing and ray-tracing PHY layer models for indoor environment. Schmitz and Weing [Schmitz06] have described the effects on AODV of the TRG and photon based propagation environment for indoor MANETS. Aaron and Weng [Aaron01] have analysed the energy constraints of indoor MANETS using the Lognormal Shadowing model. However, the ITU-R and WINNER pathloss models have not been tested for indoor simulation environment. This study extends the *ns-2* simulation environment with these models and the results have been analysed for AODV and OLSR protocols with RWP mobility and with 10 nodes.

6.4. Simulation Environment

The main aim of this study was to investigate the impact of various path loss conditions in an indoor environment. We used the Bonnmotion tool to generate mobility files for indoor scenarios with RWP mobility pattern for varying pause times in a fixed indoor flat area of 30x80 (considering sports hall or large conference room) meters and varying pause time (i.e. mobility level) from 100 to 500 (i.e. almost static conditions) in steps of 100 secs. Each result is an average of ten simulation runs with identical input parameters but with different random seed.

Some of the common simulation parameters are shown in Table 6.1.

Table 6.1: Simulation Parameters for AODV-OLSR indoor performance analysis

Parameter	Value
Simulation time	500 secs
Area size	30x80 m
Mean speed	1.5 m sec ⁻¹
No. of nodes	10
Mobility model	Random Waypoint
Pause time	100,200,300,400,500 (secs)
Traffic type	CBR
Packet size	512 bytes
Buffer size	50
Connection rate	8 pkts sec ⁻¹
Channel frequency	2.412 GHz
ITU Model	N=30, Lf=11
Transmitter power	8.6 dBm
Tx and Rx antenna Gain (Gt=Gr)	1
Received power threshold (<i>Rx_Threshold</i>)	-84.5 dBm
Carrier sense threshold (<i>CS_Threshold</i>)	-84.5 dBm

6.5. Results & Discussion

The following sections cover the discussion about the produced results.

6.5.1. Packet Delivery Ratio

The first analysis is based on varying the pause time from 100 to 500 in steps of 100 secs. The PDR shown in figure 6.1 reveals that AODV performs better than OLSR with all path loss conditions. The performance of AODV and OLSR is better if the channel conditions behave like WINNER model. There is clear network performance degradation with both routing strategies if the channel acts like ITU-R channel conditions for all pause times. There is little systematic effect on the performance of AODV and OLSR with varying pause times (i.e. mobility level changes). The PDR values achieved with ITU path loss environment are not suitable for viable MANET application as majority of the packets are lost due to poor propagation conditions.

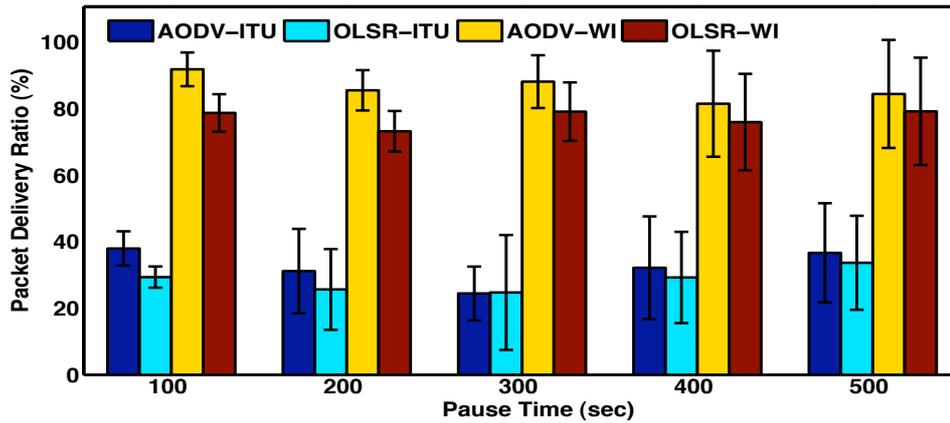


Figure 6.1: PDR vs Pause Time

6.5.2 Normalized Routing Load

We observe that network experiences significantly high NRL (see Figure 6.2) with OLSR for ITU channel conditions (see Figure 6.2). In a typical indoor wireless environment, fading and multipath conditions severely affect the received signal strength. OLSR is a proactive protocol that keeps routing tables updated periodically on nodes. However when the channel conditions get poor such as in the ITU model, these updates get faded sooner due to arbitrary topology changes. The performance of AODV is significantly better with much lower routing load, which is a key factor in scalable adhoc networks.

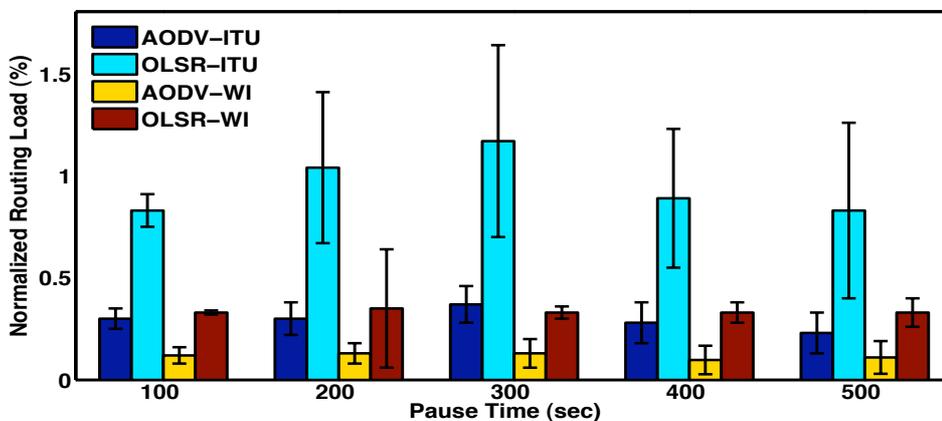


Figure 6.2: NRL vs Pause Time

6.5.3 Mean end-to-end Delay

Comparing the Mean Delay with increasing pause time, OLSR shows better performance than AODV under various channel conditions (see Figure 6.3). The network experiences significantly higher delays with AODV if the channel behaves like ITU path loss conditions. Delay is generally lower in proactive protocols due to availability of routes as and when needed. However, this difference is significant with reactive protocol such as AODV if the channel acts like ITU model.

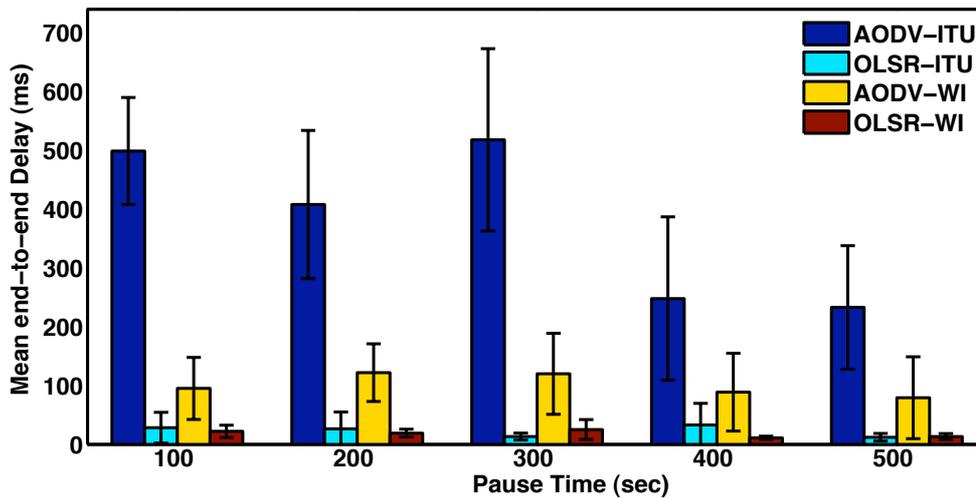


Figure 6.3: Mean Delay vs Pause Time

6.6. Testbed vs Simulation: An indoor MANET performance comparison

In Chapter 2, some discussion was made about the use of simulation tools over testbed studies in MANET research field. For outdoor cases, there have been very few testbed studies conducted compared with simulation based work mainly due to cost and inherent lack of flexibility in testbed environment. As the network size grows, these factors particularly hinder the construction of

MANET testbeds. Among all existing testbed networks, some are mentioned below

-ORBIT: This project has been established and managed by Rutgers University [Raychaudhuri05], USA and consists of indoor (400 nodes) and outdoor (50 nodes) static nodes. So, this testbed does not deal with mobility related issues. Figure 6.4 shows the ORBIT testbed constructed on a 20x20 nodes grid in an indoor environment.



Figure 6.4: ORBIT testbed grid of 400 nodes (from [Raychaudhuri05])

-APE testbed: This testbed was constructed with 37 IEEE 802.11 nodes. The APE project [Lundgren02] has also developed APE software tool that supports many major MANET routing protocols in testbed environment and is specific hardware/software dependent (i.e. few wifi LAN cards are supported).

NRL testbed: The ad hoc wireless testbed at UCLA [NRL03] consists of about twenty laptops and 60 PDAs equipped with IEEE 802.11 cards running the Linux operating system and supports unicast MANET routing protocols such as DSDV.

However, there is still a need for a scalable mobile adhoc network to be built for testing and development of new MANET routing techniques and

applications and specifically targeting mobility and propagation environment. This portion covers some of the shortcomings of the MANET testbeds by constructing a small test bed of three nodes in an indoor environment. Results of the MANET testbed are then compared with the *ns-2* based simulation results using ITU propagation model for indoor environment. AODV-UU [AODV-UU02], which is an implementation of AODV protocols in Linux kernel environment, was used in the testbed environment.

6.7. Literature Survey

Since AODV is one of the most commonly used routing protocols in MANETS, there have been many implementations of AODV developed for testbeds such as AODV-UU, MAdhoc, AODV-USCB [Chakeres04] etc. Kuladinithi *et al* [Kuladinithi04] describe the performance of a 6 nodes MANET testbed running on AODV-UU in a static environment. Sari *et al* [Sari05] published the results of a hybrid MANET testbed environment based upon AODV-UU protocol. Elis *et al* [Elis12] discusses the MANET performance on staircases with both static and dynamic cases. However, the abovementioned studies have not compared the testbed results with simulation-based results (such as *ns-2*), which is the main source of MANET routing studies. This part of the chapter covers comparison of testbed results with simulation-based results using ITU-R indoor models.

6.8. Methodology

The experimental set up was performed indoors with three laptops (two Samsung N 130 and one sony vaio NR38E) in a covered area of 25x40 meters located in the University of Leicester main engineering building. All

laptops were configured in IEEE 802.11 adhoc mode with 15 dBm transmission power. AODV-UU was running on each laptop with its default parameters. LoS and NLoS conditions were investigated with various levels of mobility, e.g. static, Tx moving and all three nodes moving conditions. A burst of ping packets (100 pkts/sec for 10 seconds) was implemented for four communication sessions among nodes in each experiment. Random mobility patterns were applied with two lab fellows and myself moving around with laptops. Figure 6.5 shows the distribution of communication session runs among nodes. One node was selected as transmitter (Source) and the two other nodes were selected as receiver (Destination) for all scenarios.

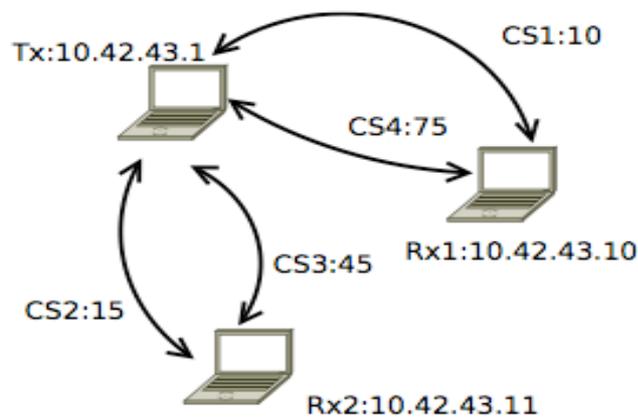


Figure 6.5: Source/Destination Distribution for a 100 second testbed/simulation run with respected Communication Session (CS) start time in secs.

For all topology conditions, the experiment was repeated five times and average results are presented. The experiment was conducted during daytime with some people movement in the testbed area. Other factors such as orientation of laptops, laptop height from ground (was kept about 1 meter above ground) may also have affected the results but are not considered during this study. Data was captured with *tcpdump* utility and was later

analysed with the *wireshark* tool to produce network performance metrics such as Packet Delivery Ratio (PDR), Mean Delay and No. of Routing Packets (RL). Ping utility provides statistics about packet loss ratio that was used to calculate PDR. *tcpdump* records all communication on wireless interface, which was later, analyzed for Routing Packets calculations. For each communication session, Mean Delay was counted by Ping tool. The ping tool reports the Round Trip Time (RTT) with minimum, average and maximum values as well as the standard deviation for individual packets in each communication session. RTT is the time difference between the receipt of the acknowledgement from the destination node to the source node, and the time of sending of the original packet at the source node. Packets within a single 10 sec long communication session were sent at a regular rate of 100pkts/s. Each scenario was repeated five times and these statistics were averaged. Simulation work was done using ns-allinone-2.34 simulator with CMU monarch wireless extension. Again each simulation result is an average of five simulation runs with identical conditions but with different random seed. The simulation is run with changing physical layer environment for Lognormal Shadowing and ITU-indoor Channel conditions for Line of Sight (LoS) and Non Line of Sight (NLOS) scenarios. Figure 6.6 shows the snapshots of indoor testbed environment along with the hardware used. The indoor lab conditions encountered with lots of objects around to obstruct the wireless signals making it more challenging to establish reliable ad-hoc network can be seen in Figure 6.6.



Figure 6.6: Left: Testbed Environment (University of Leicester Engineering Lab), Right: Laptops used for Testbed.

Some of the common simulation and experimental parameters implemented are shown in table 6.2.

Table 6.2: Simulation/Testbed Parameters

Parameter	Value
Run time	100 secs
Area size	25x 40 m
Mean speed	1 m sec ⁻¹
Traffic type	Ping
Packet size	512 bytes
Connection rate	100 pkts sec ⁻¹
No. of Connections	4
Channel frequency	2.412 GHz
Lognormal shadowing	$\beta = 1.8-4$
indoor LoS-NLoS	$\sigma_{dB} = 7$
ITU indoor Model	$N_{LoS} = 30$
Power loss coefficient	$N_{NLoS} = 35$
Transmitter power	15 dBm
Tx and Rx antenna Gain (Gt=Gr)	1
Received power threshold (RXThreshold)	-84.5 dBm
Carrier sense threshold (CSThreshold)	-84.5 dBm

6.9. Results and discussion

Simulation and testbed based results comparison has been discussed in the following sections.

6.9.1. Packet Delivery Ratio

Figure 6.7 shows the PDR for three scenarios with testbed and simulation results for LoS and NLoS case respectively. It is evident that for an indoor-LoS case, the simulation results do not change with the various topologies (i.e. PDR is constant at 100%). However there is a slight performance decrease with test bed results as mobility is introduced in the environment. For NLoS case, simulation analysis with Shadowing and ITU-R models show slight variation in results as mobility is introduced.

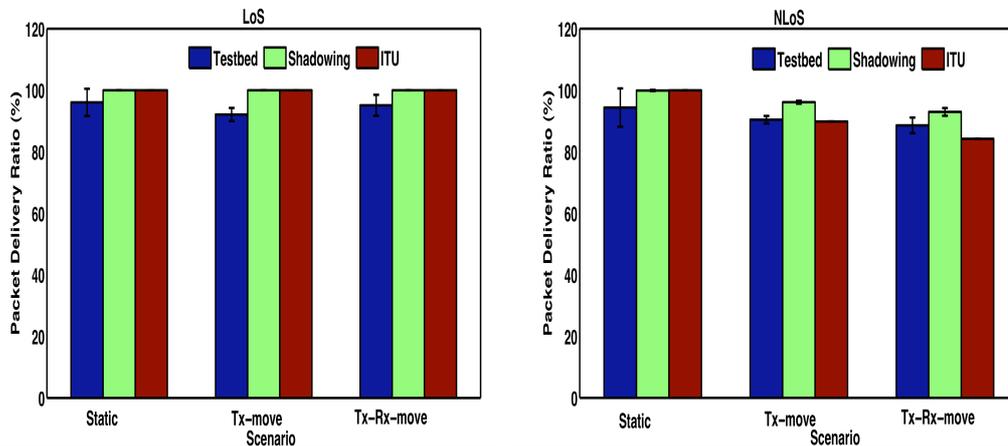


Figure 6.7: packet delivery ratio vs. mobility scenarios for LoS (left) and NLoS (right) scenarios

6.9.2. Routing load

Figure 6.8 shows the routing load comparison for simulation and testbed results with various node mobility scenarios and propagation models. With all nodes moving in LoS scenario (i.e. Tx-Rx-move), the standard deviation for testbed results is relatively high. With NLoS scenario, AODV performs better under ITU Channel conditions for all topology patterns since Shadowing conditions significantly impair the channel quality and hence the protocol

performance in NLoS case. The routing load is significantly higher with simulation results than with testbed results in NLoS scenario.

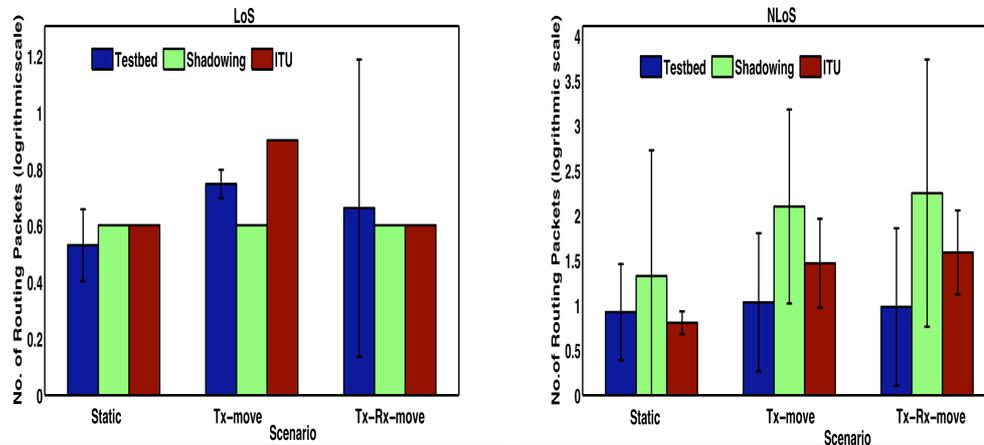


Figure 6.8: No. of Routing Packets vs. mobility scenarios for LoS (left) and NLoS (right) scenarios

6.9.3. Round Trip Delay

From figure 6.9, it can be readily observed that delay is higher for the testbed than with simulation environment analysis. In NLoS static scenario, network performance is poorer than with mobility-induced cases. It is evident that in an indoor scenario, mobility helps in reducing delay between communicating nodes, as nodes may get closer with each other in NLoS scenario.

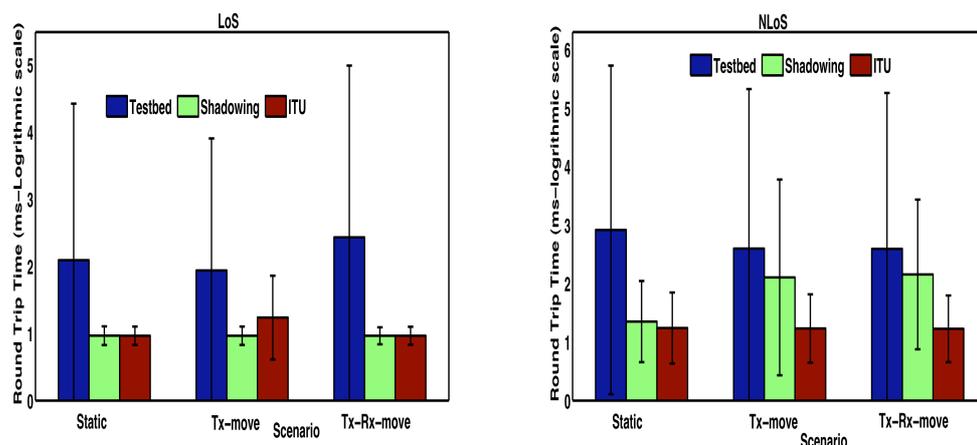


Figure 6.9: Round Trip Time vs. mobility scenarios for LoS (left) and NLoS (right) scenarios

6.10. Summary

This study focuses on indoor MANET performance analysis study covering proactive and reactive routing algorithms based upon simulation and simulation/testbed environment with varying path loss conditions. The first part of this study covers the performance comparison of AODV and OLSR protocol under influence of ITU and WINNER indoor path loss conditions. AODV performs better than OLSR considering PDR and NRL parameters under both channel environments. The network performance is generally better if the channel behaves like the WINNER model. The MANET has significantly lower Mean Delay with OLSR protocol. In the second part of this chapter, testbed and simulation results have been presented for AODV-UU protocol in an adhoc network environment. ITU-R indoor propagation model has been introduced in ns-2 simulation environment and comparison has been made with Lognormal shadowing propagation model and with testbed results. From results, it is clear that network undergoes little performance change with both propagation conditions for LoS simulation environment. There is higher routing load observed with simulation results in NLoS case. The RTT delay is much higher for LoS and NLoS condition in testbed environment than with simulation.

Chapter 7

Conclusion & Future Work

This study has investigated wireless propagation and mobility models for MANETS using *ns-2* simulation environment. ITU path loss models for indoor and outdoor scenarios along with a variety of synthetic mobility models have been simulated with varying parameters such as node density, pause time, network traffic and transmission ranges. The work done as part of this study includes simulation analysis of very large ad-hoc network (i.e. up to 1000 nodes) in the presence of varying pathloss environments with the impact of corner loss effects typically found in urban structures. For the indoor case, results from a small testbed have been compared with the *ns-2* simulation based results with the effects of ITU and TRG PHY layer environment.

7.1. Summary of Results

Summaries of key results obtained from this study are listed below.

- Slow fading environments modelled by Log-normal Shadowing strongly weaken the network performance in MANETS. MANET performance is highly dependent on mobility behaviour adopted by nodes. Nodes moving according to RPGM model tend to have better network connectivity and perform well under slow and fast channel fading environment. MG mobility pattern affects badly the network performance with nodes experiencing low connectivity due to restricted lane movement (i.e. average node connectivity is lesser than

other mobility models as shown in Figure 3.3) and hence drastically degrades the network performance.

- In urban LoS scenarios, the network performance is generally better if the communication channel is like TRG model. There is a performance degradation of about 7% and 12 % if the channel acts like GOA-LoS or ITU-LoS conditions respectively.
- MANET *ns-2* based simulations consider flat area without any obstacles. Whereas in real world scenarios, MANETS are likely to be deployed in urban built-up areas with effects of buildings and obstacles that may strongly hinder free space communication. The effect of increasing the number of obstacles in the network field along with modified TRG, ITU and Shadowing loss models have confirmed these concerns.
- RWP mobility model related node distribution issues have been looked upon in the literature extensively. However this effect degrades the performance of DSR protocol significantly with increasing number of nodes (specifically after 75 nodes). The network experiences significantly higher routing load and low PDR in comparison with AODV protocol.
- The RPGM model has been used to mimic group mobility in MANET scenarios. However effect of changing the mobility pattern adopted by group-heads has not been examined in the literature. This study investigates the leader's mobility behaviour adopted by respective cluster heads and its crucial

impact on MANET routing performance has been analysed. Simulation results confirm that the leaders mobility patterns strongly influence the network performance in MANETS.

- Scalability of routing protocols has been analysed in the presence of simple PHY layer environment such as Free Space model for up to 10,000 nodes in literature. However, modelling the PHY layer for urban LoS/NLoS scenarios drastically affects the produced results.
- The impact of node density is more severe with TRG model than with ITU models in scalable adhoc networks.
- AODV and OLSR suffer poor network performance if the channel conditions are like ITU path loss model in an indoor simulation environment.
- For indoor testbed & simulation results analysis, it has been observed that there is very little difference between the simulation results and testbed results for LoS & NLoS scenarios tested through a small testbed of 3 nodes.
- There is a higher routing load observed with simulation results in NLoS scenario than with real testbed results. This factor is important when considering the scalability of routing. As routing load is the most important aspect in scalability of MANETS, false simulation results can mislead and hamper the routing ability in very large adhoc networks.

- The RTT calculated in real time systems is significantly higher than what was observed in simulation based studies that place a question mark on the confidence in simulation results.

7.2. Directions for Future Work

Through this research, several interesting issues have come forward that require further investigation.

- This study has covered the majority of synthetic mobility models ranging from random to temporal, spatial and geographic based mobility patterns. However other synthetic and trace based mobility models have not been looked upon in this work. A possible line of research would extend the simulation analysis to a broader range of mobility models under varying propagation loss models.
- This research presented the analysis of state of the art reactive routing schemes such as AODV and DSR for MANET outdoor scenario and OLSR for indoor environment. This work can be extended to analyse the performance of further proactive, reactive and hybrid routing protocols for a variety of indoor/outdoor propagation and mobility environments.
- The use of appropriate propagation models has been thoroughly investigated by using fading, ITU, GOA-adhoc and modified TRG models in various scenarios. However, there is still a demand to develop a propagation

model that should have been derived from purely MANET testbed scenarios for urban, suburban and rural cases.

- *ns-2* has been used as a simulation tool during the entire course of this study. However, it will be motivating to apply same scenarios using other simulators such as GLoMoSim, Qualnet etc.

- *ns-2* is the most popular tool available freely for MANET research community. There have been few attempts to add geographic based simulation environment in *ns-2*. However, a possible future work can be done by adding more realistic geographical settings such as integrating google maps and realising geography based effects with respect to propagation modelling.

- There have been various testbed studies reported in literature with purpose of investigating MANET routing performance. However, large-scale indoor/outdoor testbed work in comparison with simulation based analysis has not been reported in literature. A possible future direction is to analyse the validity of simulation work with testbeds in large adhoc networks.

- CBR packets have been used as a traffic source through the course of this study. It would be useful to analyse MANET performance under different traffic patterns such as those generated by Transmission Control Protocol.

References

[Aaron01] A. Aaron, J. Weng, "Performance Comparison of Ad-hoc Routing Protocols for Networks with Node Energy Constraints", available at <http://ivms.stanford.edu> , Class Project, Spring 2001.

[Alshanyour10] A. Alshanyour, U. Baroudi , "A simulation study: the impact of random and realistic mobility models on the performance of bypass-AODV in ad-hoc wireless networks", EURASIP Journal on Wireless Communications and Networking, 2010.

[Anuj10] K. Anuj, H. Sadawarti and K. Anil, "Performance analysis of AODV, DSR & TORA Routing Protocols", IACSIT International Journal of Engineering and Technology, Vol. 2(2), pp.226-231, 2010.

[AODV-UU02] AODV-UU Implementation, <http://core.it.uu.se/core/index.php/AODV-UU> , December 2002. Last accessed on June, 2012.

[Aschenbruck07] N. Aschenbruck, G. Padilla, Elmar, Gerharz, Michael, Frank, Matthias und Martini and Peter, "Modelling Mobility in Disaster Area Scenarios", In: Proc. 10th ACM-IEEE Int. Symposium on Modelling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM) (2007), S. 4–12, 2007.

[Bai04] F. Bai and A. Helmy, "A Survey of Mobility Modelling and Analysis in Wireless Adhoc Networks", Book Chapter in the book "Wireless Ad Hoc and Sensor Networks", Kluwer Academic Publishers, June 2004.

[Bettstetter01] C. Bettstetter, "Smooth is better than sharp: A random mobility model for simulation of wireless networks", In Proceedings of MSWiM'01. ACM, July 2001.

[Bettstetter02] C. Bettstetter and C. Wagner, "The Spatial Node Distribution of the Random Waypoint Mobility Model", In: Proceedings of the 1st German Workshop on Mobile Ad-Hoc Networks, pp.41-58, 2002.

[Bindral10] H. S. Bindral, S. K. Maakar and A. L. Sangal, "Performance Evaluation of Two Reactive Routing Protocols of MANET using Group Mobility Model", IJCSI International Journal of Computer Science Issues, Vol. 7, Issue 3, No 10, May 2010.

[Bonnmotion09] Bonnmotion: mobility Scenario Generation and Analysis Tool, University of Bonn, Institute of Computer Science, June 2009.

[Boukerche08] A. Boukerche, "Algorithms and Protocols for Wireless, Mobile Ad Hoc Networks", Wiley-IEEE Press | 2008 | ISBN: 0470383585 |, 2008.

[Boukerche04] A. Boukerche, "Performance Evaluation of Routing Protocols for Ad Hoc Wireless Networks", *Mobile Networks and Applications* 9, 333–342, Kluwer Academic Publishers. Manufactured in The Netherlands, 2004.

[Broach98] J. Broch, D. A. Maltz, D. B. Johnson, Y. C. Hu and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols", *Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom98)*, ACM, October 1998.

[Camp02] T. Camp, J. Boleng and V. Davies, "A survey of mobility models for ad hoc network re-search", *Wireless Comm. and Mobile Computing (WCMC)*, 2(5): 483–502, 2002.

[Cavilla07] L. Cavilla, G. Baron, T.E. Hart, L. Litty and E. de-Lara, "On the robustness of simple indoor MANET simulation models", *Ad hoc & sensor wireless networks*, 2007.

[Cavilla04] L. Cavilla, G. Baron, L. Litty, E. de-Lara, "Simplified simulation models for indoor MANET evaluation are not robust", in: *Proceedings of SECON*, 2004.

[Chakeres04] I. D. Chakeres, E. M. Belding-Royer, "AODV routing protocol implementation design", *Distributed Computing Systems Workshops*, 2004. *Proceedings. 24th International Conference on*, vol., no., pp. 698- 703, 23-24 March 2004.

[Chen07] Q. Chen, F. Schmidt-Eisenlohr, D. Jiang, M. Torrent-Moreno, L. Delgrossi and H. Hartenstein, "Overhaul of ieee 802.11 modeling and simulation in ns-2", In *MSWiM '07: Proceedings of the 10th ACM Symposium on Modeling, analysis, and simulation of wireless and mobile systems (2007)*, pp. 159-168, 2007.

[Chiang98] C. Chiang, "Wireless Network Multicasting", Los Angeles: PhD thesis, University of California, 1998.

[Cichon99] D. J. Cichon and T. Kurner, "Propagation prediction Models", *COST 231 Final Report*, ch.4.p.134, 1999.

[CMU99] The CMU Monarch Project's Wireless and Mobility Extensions to ns, <http://www.monarch.cs.cmu.edu/>. Last accessed on March 2012.

[Das00] S. R. Das, C. E. Perkins and E. M. Royer, "Performance comparison of two on-demand routing protocols for ad hoc networks", in *Proc. INFOCOM 2000*, pp. 3-12, 2000.

[David03] O. J. David, "Performance Comparison of MANET Routing Protocols In Different Network Sizes", *Computer Science Project*, University of Berne, Switzerland, 2003, Available at

http://cds.unibe.ch/research/pub_files/Joe04.pdf, Last Accessed on July, 2012.

[Davies01] V. Davies, "Evaluating Mobility Models Within an Ad Hoc Network", Master's thesis, Colorado School of Mines, Colorado, 2000. Communications (ICC), 2001.

[Djenouri05] D. Djenouri, L. Khelladi, and N. Badache, "A survey of security issues in mobile ad hoc and sensor networks," IEEE Commun. Surveys Tutorials, vol. 7, pp. 2–28, 2005.

[Dricot03] J. Dricot, P. D. Doncker, E. Zimanyi and F. Grenez, "Impact of the physical layer on the performance of indoor wireless networks," in Proc. Int. Conf. Software, Telecommunications Computer Networks, SOFTCOM, pp.872-876, Split, Croatia, Oct. 2003.

[Einstein06] A. Einstein, "Zur theorie der brownischen bewegung", Journal: Annalen Der Physik - ANN PHYS-BERLIN, vol. 324, no. 2, pp. 371-381, 1906.

[Elis12] K. Elis, M. Hiyama, M. Ikeda and L. Barolli, "Performance comparison of OLSR and BATMAN routing protocols by a MANET testbed in stairs environment". Computers & Mathematics with Applications 63(2): 339-349, 2012.

[Eltahir07] I. K. Eltahir, "The Impact of Different Radio Propagation Models for Mobile Ad hoc NETWORKS (MANET) in Urban Area Environment", Wireless Broadband and Ultra Wideband Communications, 2007. AusWireless 2007. The 2nd International Conference on, vol., no., pp.30, 27-30 Aug. 2007.

[ETSI98] European Telecommunications Standards Institute (ETSI): Universal Mobile Telecommunications System (UMTS) - Selection procedures for the choice of radio transmission technologies of the UMTS. UMTS 30.03 version 3.2.0, TR 101 112. 1998.

[Feuerstein94] M. J. Feuerstein, K. L. Blackard, K.L. T. S. Rappaport, S. Y. Seidel and H. H. Xia, "Path loss, delay spread, and outage models as functions of antenna height for microcellular system design", Vehicular Technology, IEEE Transactions on, vol.43, no.3, pp.487-498, Aug 1994.

[Friis46] H. T. Friis, "Simple transmission formula", PROC. I.R.E., vol. 34, pp. 254-256 (transmission efficiency in space, expressed in terms of effective area); May, 1946.

[Gast02] M. S. GAST, "802.11 Wireless Networks: The Definitive Guide": O'REILLY, 2002.

[Goldsmith05] A. Goldsmith, "Wireless Communications", Cambridge University Press, 2005.

[Green02] D. B. Green, M. S. Obaidat, "An Accurate Line of Sight Propagation Performance Model for Ad-Hoc 802.11 Wireless LAN (WLAN) Devices", Proceedings of IEEE ICC 2002, New York, April 2002.

[Gruber04] I. Gruber, O. Knauf and H. Li "Performance of Ad Hoc Routing Protocols in Urban Environments", European Wireless 2004, Feb 2004.

[Guerian87] R. A. Guerian, "Channel occupancy time distribution in a cellular radio systems", Vehicular Technology, IEEE Transactions, 89-99, 1987.

[Hamida09] E. B. Hamida, G. Chelius and J. M. Gorce, "Impact of the Physical Layer Modeling on the Accuracy and Scalability of Wireless Network Simulation SIMULATION", September 2009 85: 574-588, first published on June 29, 2009.

[Harminder10] S. B. Harminder, S. K. Maakar and A. L. Sangal, "Performance Evaluation of Two Reactive Routing Protocols of MANET using Group Mobility Model", IJCSI International Journal of Computer Science Issues, Vol. 7(10), pp.38-43, 2010.

[Harrold00] T. J. Harrold and A. R. Nix, "Intelligent relaying for future personal communication systems", Capacity and Range Enhancement Techniques for the Third Generation Mobile Communications and Beyond (Ref. No. 2000/003), IEE Colloquium on , vol., no., pp.9/1-9/5, 2000.

[Harrold01] T. J. Harrold, A. R. Nix and M. A. Beach, "Propagation studies for mobile-to-mobile communications", Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th , vol.3, no., pp.1251-1255 vol.3, 2001.

[Hata97] M. Hata, "A Report on Technology Independent Methodology for the Modeling, Simulation and Empirical Verification of Wireless Communications System Performance in Noise and Interference Limited Systems Operating on Frequencies between 30 and 1500MHz", TIA TR8 Working Group, IEEE Vehicular Technology Society Propagation Committee, May 1997.

[Haykin05] S. Haykin and M. Moher, "Modern Wireless Communications", ISBN 0-13- 124697-6, Prentice Hall, 2005.

[Henderson08] T. Henderson, D. Kotz and I. Abyzov, "The changing usage of a mature campus-wide wireless network", Computer Networks, 52(14):2690-2712, 09 October 2008.

[Hong02] X. Hong, K. Xu and M. Gerla, "Scalable routing protocols for mobile ad hoc networks", Network, IEEE , vol.16, no.4, pp.11-21, Jul/Aug 2002.

[Hong99] X. Hong, M. Gerla, G. Pei and C. Chiang, "A Group Mobility Model for Ad Hoc Wireless Networks" In: Proc. of the ACM Int. Workshop on Modelling and Simulation of Wireless and Mobile Systems (MSWiM) (1999), S. 53-60, 1999.

[IEEE07] “IEEE Standard for Information technology telecommunications and information exchange between systems local and metropolitan area networks specific requirements”, IEEE Computer Society, New York, 2007.

[IETF97] <http://www.ietf.org/dyn/wg/charter/manet-charter.html>, Last accessed on December, 2011.

[ITU-R 1238] ITU-R P.1238-6, “Propagation data & Prediction methods for the planning of indoor radio communication systems & radio local area networks in the frequency range of 900 MHz to 100GHz”, October 2009.

[ITU-R 1411] ITU-R P.1411-5, “Propagation data & Prediction methods for the planning of short range outdoor radio communication systems & radio local area networks in the frequency range of 300 MHz to 100GHz”, December 2009.

[Jardosh05] A. P. Jardosh, E. M. Belding-Royer, K. C. Almeroth and S. Suri, “Real-world environment models for mobile network evaluation”, Selected Areas in Communications, IEEE Journal vol.23, no.3, pp. 622- 632, March 2005.

[Jayakumar08] G. Jayakumar and G. Ganapathi, “Reference point group mobility and random way-point models in performance evaluation of MANET routing protocols,” Journal of Computer Systems, Networks, and Communications, vol. 2008, Article ID 860364, 10 pages, 2008.

[Jingfang09] S. Jingfang, W. Muqing and J. Wen , “Comprehensive Evaluation of AODV in Wireless Multi-Hop Ad Hoc Networks”, Wireless Communications, Networking and Mobile Computing, 2009. WiCom '09. 5th International Conference on , vol., no., pp.1-4, 24-26 Sept. 2009.

[Joerer12] S. Joerer, F. Dressler, and C. Sommer, “Comparing Apples and Oranges? Trends in IVC Simulations”, in ACM VANET 2012, Low Wood Bay, Lake District, UK, pp. 27–32 , June 2012.

[Johnson98] D. Johnson, D. A. Maltz and J. Broch, “The dynamic source routing protocol for mobile ad hoc networks (Internet-draft)” , in: Mobile Ad-hoc Network (MANET) Working Group, IETF 1998.

[Jones01] C. E. Jones, K. M. Sivalingam, P. Agrawal and J. C. Chen, “A survey of energy efficient network protocols for wireless networks”, ACM/Baltzer Wireless Networks, 7(4) 343–358, 2001.

[Keränen09] A. Keränen A, J. Ott and T. Kärkkäinen, “The ONE simulator for DTN protocol evaluation”, in: SIMUTools '09: Proceedings of the 2nd International Conference on Simulation Tools and Techniques, 2009.

[Khan09] Khan, A.; Sadhu S. & Yeleswarapu M. (2009). A comparative analysis of DSRC and 802.11over Vehicular Ad hoc Networks. *Project Report*,

Department of Computer Science, University of California, Santa Barbara, pp.1–8, 2009.

[Kotz05] D. Kotz and D. T. Henderson, “CRAWDAD: A Community Resource for Archiving Wireless Data at Dartmouth”, *Pervasive Computing, IEEE* , vol.4, no.4, pp. 12- 14, Oct.-Dec. 2005.

[Kuan06] H. O. Kuan, H. L. Ong, E. R. Tee and R. Sureswaran, “Scalability study of ad-hoc wireless mobile network routing protocol in sparse and dense networks”, *Distributed Frameworks for Multimedia Applications*, 2006. The 2nd International Conference on, vol., no., pp.1-8, May 2006.

[Kuladinithi04] K. Kuladinithi, A. Udugama, N. Fikouras and C. Görg, “Experimental Performance Evaluation of AODV implementations in Static Environment”, 59th IETF – Seoul, South Korea, February29 -March4, 2004.

[Kurkowski05] S. Kurkowski, T. Camp and M. Colagrosso, “ MANET Simulation Studies: The Incredibles”, *SIGMobile Mobile Computing and Communications Review*, Volume 9, Number 4, pp. 50-61, 2005.

[Kyosti07] P. Kyosti et al., “WINNERII Channel Models,” WINERII Public Deliverable, Sep. 2007.

[Lee03] S. Lee, E. M. Belding-Royer and C. E. Perkins, “ Scalability study of the ad hoc on-demand distance vector routing protocol”, *International Journal on Network Management*, 13(2), March-April 2003.

[Lee86] W. Lee, “Mobile Communications Design Fundamentals”, Indianapolis, Indiana: Howard W. Sams & Co, p.66 , 1986.

[Liang99] B. Liang, and Z. Haas, "Predictive distance-based mobility management for PCS networks." *Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, March 1999.

[Lohier12] S. Lohier, A. Rachedi, E. Livolant and I. Salhi, “Wireless Sensor Network simulators relevance compared to a real IEEE 802.15.4 Testbed”, *IJAACS*, January,2012.

[Lundgren02] H. Lundgren, D. Lundberg, J. Nielsen, E. Nordstrom and C. Tschudin, “A large-scale testbed for reproducible ad hoc protocol evaluations”, *Wireless Communications and Networking Conference*, 2002. WCNC2002. 2002 IEEE , vol.1, no., pp. 412- 418 vol.1, 17-21 Mar 2002.

[Mangel11] T. Mangel, O. Klemp, and H. Hartenstein, “ 5.9 GHz Inter-Vehicle Communication at Intersections. A Validated Non-Line-of-Sight Path-Loss and Fading Model”, *EURASIP Journal on Wireless Communications and Networking*, 2011.

[Misra05] R. Misra and C. R. Mandal, "Performance Comparison of AODV/DSR On- demand Routing Protocols for Ad Hoc Networks in Constrained Situation", ICPWC, 2005.

[Mittal09] S. Mittal and P. Kaur, "Performance comparison of AODV, DSR and ZRP routing protocols in MANETs", Proceeding of the 2009 International Conference on Advances in Computing, Control and Telecommunication Technologies, Dec. 28-29, Trivandrum, Kerala, India, 2009.

[Mobisim10] Mobisim v2, A Framework to Manage Mobility Models, Sharif University of Technology, 2006-2010.

[Mustafa09] E. Mustafa, "Mobile broadband: including WiMAX and LTE", Springer Verlag, 2009.

[Mogensen91] P. Mogensen, P. Jensen, and J. Andersen, "1800 MHz Mobile Net Planning Based on 900 MHz Measurements", COST 231 TD (91)-08, Firenze, Jan 1991.

[Mousavi07] S. M. Mousavi, H. R. Rabiee, M. Moshref and A. Dabirmoghaddam, "MobiSim: A Framework for Simulation of Mobility Models in Mobile Ad-Hoc Networks", Wireless and Mobile Computing, Networking and Communications, 2007. WiMOB 2007. Third IEEE International Conference on , vol., no., pp.82, 8-10 Oct. 2007.

[Nakagami60] M. Nakagami, "The m-distribution—A general formula for intensity distribution of rapid fading", In W. G. Hoffman, editor, Statistical Methods in Radio Wave Propagation. Pergamon, Oxford, U.K., 1960.

[Naseef10] L. Nassef, "On the effect of fading and mobility in on-demand routing protocols", Elsevier Egyptian Informatics Journal, 11 (2) , 2010.

[Natarajan,10] M. Natarajan, "A simulation study on the impact of mobility models on the network connectivity, hop count and lifetime of routes for ad hoc networks", Informatica (Ljubljana), v 34, n 2, p 207-221, June 2010.

[ns-2-08] "The Network Simulator ns-2", version ns-2.34, <http://www.isi.edu/nsnam/ns/doc>. Accessed first October 2008.

[ns-3-12] ns-3. <http://www.nsnam.org/>, Last Visited August 21, 2012.

[NRL03] NRL Mobile Network Emulator, Naval Research Laboratory, Washington DC, January 24, 2003.

[Ofcom07] <http://stakeholders.ofcom.org.uk/binaries/research/technology-research/finalreportph2.pdf> , published in October 2007.

[Papageorgiou09] C. Papageorgiou, K. Birkos, T. Dagiuklas and S. Kotsopoulos, "Simulating Mission Critical Mobile Ad Hoc Networks", 12-th ACM International Conference on Modeling, Analysis and Simulation of

Wireless and Mobile Systems (MSWiM) - Tenerife, Canary Islands, Spain 2009.

[Patwari99] N. Patwari, G. D. Durgin, T. S. Rappaport and R. J. Boyle, "Peer-to-peer low antenna outdoor radio wave propagation at 1.8 GHz", Vehicular Technology Conference, 1999 IEEE 49th , vol.1, no., pp.371-375 vol.1, Jul 1999.

[Perkins03] C. E. Perkins, B. Royer and S. Das, "Ad hoc On- Demand Distance Vector (AODV) Routing", RFC 3561, 2003.

[Perkins01] C. E. Perkins, "Ad Hoc Networking", ch. 3. Addison Wesley, 2001.

[Rango11] F. D. Rango, F. Veltri and P. Fazio, "Interference aware-based ad-hoc on demand distance vector (ia-aodv) ultra wideband system routing protocol", Comput Commun 34(12):1475–1483, 2011.

[Rao09] K. R. Rao, Z. S. Bojkovic and D.A. Milovanovic, "Wireless Multimedia Communications: Convergence, DSP, QoS, and Security", CRC Press, 2009.

[Rappaport96] T. S. Rappaport, "Wireless communications, principles and practice", Prentice Hall, 1996.

[Raychaudhuri05] D. Raychaudhuri, I. Seskar, M. Ott, S. Ganu, K. Ramachandran, H. Kremo, R. Siracusa, H. Liu and M. Singh, "Overview of the ORBIT radio grid testbed for evaluation of next-generation wireless network protocols", Wireless Communications and Networking Conference, 2005 IEEE , vol.3, no., pp. 1664- 1669 Vol. 3, 13-17 March 2005.

[Reddy06] P. C. Reddy, "Performance Analysis of Adhoc Network Routing Protocols", Academic Open Internet Journal, SSN 1311-4360, Volume 17, 2006.

[Rhee07] I. Rhee, M. Shin, S. Hong, K. Lee and S. Chong, "On the Levy-walk nature of human mobility: Do humans walk like monkeys?", Technical Report, North Carolina State University, 2007.

[Roy11] R. Roy and R. Ranjan, "Realistic Random Direction Mobility", Handbook of Mobile Ad Hoc Networks for Mobility Models, Springer US, Isbn: 978-1-4419-6050-4, 2011.

[Royer01] E. M. Royer, P. M. Melliar-Smith and L. E. Moser, "An Analysis of the Optimum Node Density for Ad hoc Mobile Networks", in Proceedings of the IEEE International Conference on Communications (ICC), Helsinki, Finland, June 2001.

[Royer99] E. M. Royer and C. K. Toh , "A review of current routing protocols for ad hoc mobile wireless networks", Personal Communications, IEEE , vol.6, no.2, pp.46-55, doi: 10.1109/98.760423, Apr 1999.

[Sari05] R. F. Sari, A. Syarif, K. Ramli and B. Budiardjo, "Performance evaluation AODV routing protocol on ad hoc hybrid network testbed using PDAs", Networks, 2005. Jointly held with the 2005 IEEE 7th Malaysia International Conference on Communication., 2005 13th IEEE International Conference on , vol.1, no., pp. 6 pp., 16-18 Nov. 2005.

[Schmitz04] R. Schmitz, M. Torrent-Moreno, H. Hartenstein and W. Effelsberg, "The impact of wireless radio fluctuations on ad hoc network performance", Local Computer Networks, 2004. 29th Annual IEEE International Conference on , vol., no., pp. 594- 601, 16-18 Nov. 2004.

[Schmitz06] A. Schmitz and M. Wenig, "The effect of the radio wave propagation model in mobile ad hoc networks", In Proceedings of ACM MSWiM, October 2006.

[Shlesinger93] M. Shlesinger, G. M. Zaslavsky, and J. Klafter, "Strange kinetics". Review article, Nature (London, United Kingdom), 363, 31–37 , 1993.

[Spyropoulos06] T. Spyropoulos, "Performance analysis of mobility-assisted routing", in: Proceedings of ACM MobiHoc, 2006.

[Stepanov08] I. Stepanov and K. Rothermel, "On the Impact of a More Realistic Physical Layer on MANET Simulations Results", Elsevier AdHoc Networks, vol. 6, no. 1, pp. 61–78, June 2008.

[Taliwal04] V. Taliwal, D. Jiang, H. Mangold, C. Chen, and R. Sengupta. "Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication", In VANET'04: Proceedings of the 1st ACM international workshop on vehicular adhoc networks, pages88–88, NewYork, NY, USA, 2004.

[Timcenko10] V. Timcenko M. Stojanović and S. Bostjancic Rakas, "Simulation Study of MANET Routing Protocols using Mobility Models", Computers and Simulation in Modern Science (Vol. III). – WSEAS Press, 2010. – P. 186–196.

[Thomson03] Thomas Clausen *et. al.* , "Optimized Link State Routing Protocol", <http://www.ietf.org/internet-drafts/draft-ietf-manet-olsr-11.txt>, July 2003.

[Tuteja10] A. Tuteja, R. Gujral and S. Thalia, "Comparative Performance Analysis of DSDV, AODV and DSR Routing Protocols in MANET Using NS2", ace, pp.330-333, 2010 International Conference on Advances in Computer Engineering, 2010.

[Valery05] N. Valery and G. Thomas, "Scalability of routing methods in ad hoc networks", Performance Evaluation, 62(1–4):193–209, October 2005.

[Wang08] Z. Wang, E. K. Tameh and A. R. Nix, "Joint Shadowing Process in Urban Peer-to-Peer Radio Channels", Vehicular Technology, IEEE Transactions on , vol.57, no.1, pp.52-64, Jan. 2008.

[WINNER07] IST-WINNER II Deliverable 1.1.2 v.1.2. WINNER II Channel Models, IST-WINNER2. Tech. Rep., 2007 (<http://www.ist-winner.org/deliverables.html>). Published in 2007.

[Winprop10] Winprop radio propagation suite, <http://www.awe-communications.com/>

[Wu00] S. L. Wu, C. Y. Lin, Y. C. Tseng and J. L. Sheu, "A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks", Parallel Architectures, Algorithms and Networks, 2000. I-SPAN 2000. Proceedings. International Symposium on , vol., no., pp.232-237, 2000.

[Wu11] D. Wu, J. Li and J. Liu, "A random obstacle-based mobility model for delay-tolerant networking". Int. J. Network Mgmt., 21: 326–339. doi: 10.1002/nem.793, 2011.

[Xin06] Y. Xin, "Distributed Cache Updating for the Dynamic Source Routing Protocol", IEEE Transactions on Mobile Computing, vol. 5, no. 6, pp. 609-626, June 2006.

[Yoon03] J. Yoon, M. Liu and B. Noble. "Random waypoint considered harmful", Twenty-Second Annual Joint Conference of The IEEE Computer and Communications Societies. INFOCOM 2003.

[Zang07] L.F. Zang and G. B. Rowe, "Improved modelling for mobile Ad-hoc networks", The Institute of Engineering and Technology, IEEE Electronics Letters online no: 20071530, 2007.

[Zeng98] X. Zeng, R. Bagrodia, M. Gerla, "GloMoSim: a library for parallel simulation of large-scale wireless networks", Parallel and Distributed Simulation, 1998. PADS 98. Proceedings. Twelfth Workshop on, vol., no., pp.154-161, 26-29 May 1998.

List of Publications

The following is a list of the various publications that have been produced during the course of work reported in this thesis.

- Amjad, K.; Stocker, A.J.; , “Impact of node density and mobility on the performance of AODV and DSR in MANETS,” *Communication Systems Networks and Digital Signal Processing (CSNDSP), 2010 7th International Symposium on*, vol., no., pp.61-65, 21-23 July 2010.
- Amjad, K.; Stocker, A.J.; , “Impact of slow and fast channel fading and mobility on the performance of AODV in ad-hoc networks,” Loughborough Antenna and Propagation Conference, 8-9 November 2010, Loughborough, UK.
- Amjad, K.; , “Performance Analysis of DSR Protocol under the Influence of RPGM Model in Mobile Ad-hoc Networks,” *Distributed Computing Systems Workshops (ICDCSW), 2011 31st International Conference on* , vol., no., pp.100-104, 20-24 June 2011.
- Amjad, K.; Stocker, A.J.; , “Impact of propagation loss and mobility on the performance of AODV and DSR in ad-hoc networks, “ *Wireless @ VT, 21st annual wireless symposium*, Virginia Polytechnic Institute and State University, Virginia, USA, June 1-3, 2011.
- Amjad, K.; , “MANET Indoor Performance analysis under the Influence of Dynamic Propagation Pathloss Conditions,” *The Second International Conference on Communications and Information Technology*, Taibah University, Saudi Arabia, March 23-25, 2012.
- Amjad, K.;, “From Simulation to Testbed: An Indoor MANET Performance Analysis Study,” Loughborough Antenna and Propagation Conference, 12-13 November 2012, Loughborough, UK.