HELSINKI UNIVERSITY OF TECHNOLOGY
Department of Computer Science and Engineering
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PERFORMANCE OF WIRELESS AD HOC ROUTING PROTOCOLS

A Simulation Study in Realistic Environments

Master's Thesis

Stefano Marinoni

Laboratory for Theoretical Computer Science
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To my wonderful parents

for their everlasting love and encouragement,

which I relied and enjoyed all my life.

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ABSTRACT OF
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Supervisor: Professor Hannu H. Kari
Instructor: M. Sc. Mikko Särelä

Multiple wireless devices jointly create and maintain ad hoc networks without the help of centralized wired entities of any kind. Thus, their employment is favored to happen in many environments with distinct topological characteristics. A typical place of employment is in Urban Areas.

Since the ad hoc technology is not yet massively spread, research in this area is mostly simulation based. It takes place by modeling a variety of features of the particular framework under study. The motion of the mobile terminals along with the topological characteristics of the terrain in which a network operates, are key factors in the performance of the protocol being investigated. Diversified mobility conditions and different propagation prediction methods, vary the network connectivity graph distinctively throughout the time. Hence, they both impact protocol performance.

This thesis proposes and implements a new, complete, and realistic Urban Mobility Model. The aim is to study its effect on routing performance in comparison with the more common RWP mobility fashion. The research is performed through the use of DSR as routing protocol.

The results prove that in a realistic scenario with roads and buildings, the topological features of the environment dominate the routing protocol performance. Particularly, while the presence of streets itself slightly eases the protocol's duty, the placement of buildings drastically makes it harder.

Keywords: ad hoc network, mobility model, radio signal propagation, routing, performance, manhattan, realistic simulation
Language: English

Preface

I wrote this Master's Thesis entirely at Helsinki University of Technology (HUT), working in the Laboratory for Theoretical Computer Science within the Department of Computer Science and Engineering. The particular research group which I was member of, is referred to as Mobility Management Research Group (MMRG). The thesis was meant to be submitted to the Faculty of Mathematical, Physical and Natural sciences (MM.FF.NN.) of the University of Milan in partial fulfillment of the requirements for the degree of Master of Science (Computer Science). Hence, the current work must be deemed such as an external work done during the Academic Year 04-05.

My experience at HUT started on September 2003 when I was accepted to take part in a yearly exchange program. The following year, after having taken advantage of a few theses previously written in the Mobility Area, I applied with my own proposal to start my thesis in the area concerned. The MMRG immediately showed interest towards my proposal by supporting and developing my initial ideas further. Likewise, the department council at University of Milan has also approved the topic being proposed.

My sojourn in Finland was very worth for both my social life and my career ambitions. I have to admit that my experience with MMRG was very formative. It solidified my knowledge and interests towards this novel and fascinating branch of the telecommunication technology. I learned a lot in the Network Simulation field, and I am glad to be currently part of the Mobility Management Research Group at HUT. In fact, I decided to go on working for this university as a researcher, and further collaborate with their challenging projects.

Stefano Marinoni

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I would like to express my sincere appreciation to Helsinki University of Technology for providing me with all the needed scientific resources to carry this research. I would like to specifically thank my Supervisor Professor Hannu H. Kari, and my Instructor Mikko Särelä for their invaluable support and guidance during the whole research period. It is a pleasure, as well as an honor, to collaborate with someone of their knowledge and experience.

Also, I would like to express my gratitude to Professor Gianfranco Prini who constantly showed helpfulness during these months of hard work, even the distances were preventing our direct collaboration.

I extend my thanks to my colleague Tuulia who often discussed with me about more or less technical topics during those long, dark days at the office. Further, I wish to thank Andreas, Tiina, Giuseppe and all the other friends who shared their free-time with me during this academic year.

Finally, I want to express my last but not least gratitude to my parents, without whom I would have never been able of thinking to embark on such a journey.

Helsinki May 25th 2005

Stefano Marinoni

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Abbreviations and Acronyms

3D	Three Dimensional
AODV	Ad Hoc Distance Vector
ARP	Address Resolution Protocol
CBR	Constant Bit Rate
CPU	Central Processing Unit
CSMA/CA	Carrier Sense Multiple Access - Collision Avoidance
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
DV	Distance Vector
FS	Free Space
GM	Group Motion
GPS	Global Positioning System
GSM	Global System for Mobile communications
IEEE	Institute of Electrical and Electronics Engineers
IPv4	Internet Protocol version four
LAN	Local Area Network
LOS	Line Of Sight
LS	Link State
MAC	Medium Access Control
MANET	Mobile Ad Hoc Networking
MH	Manhattan
MM	Mobility Model
MN	Mobile Node
mod	Modulo
MS	Mobile Station
ND	N Dimensional
NS2	Network Simulator 2
PDA	Personal Digital Assistant
PRW	Probabilistic Random Walk

RD	Random Direction
RE	Route Error
RM	Random Motion
RP	Reference Point
RPGM	Reference Point Group Mobility
RPM	Radio Propagation Model
RPMO	Radio Propagation Model with Obstacles
RR	Route Request
RW	Random Walk
RWP	Random Waypoint
SD	Safety Distance
SH	Shadowing
S/R	Sender - Receiver
TCP/IP	Transmission Control Protocol - Internet Protocol
TORA	Temporally Ordered Routing Algorithm
TRG	Two Ray Ground
UDP	Unreliable User Datagram Protocol
UMM	Urban Mobility Model
Wi-Fi	Wireless Fidelity
WLAN	Wireless LAN

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Chapter 1

Introduction

Nowadays ad hoc wireless networks are becoming always more popular in our everyday life. Ad hoc networks consist of a set of handset devices, usually mobile and wire free, such as notebooks, mobile phones, Personal Digital Assistants (PDAs) that exchange information between each other. They are self configuring and capable of operating without any fixed infrastructure. This, along with the fact that modern small computers (only in size) operate with hours of battery power, are the main facts which have raised high interests in the researchers community world wide.

Since in a wireless ad-hoc network the mobile devices are free to move, its topology is subject to be rather dynamic. Furthermore, considered the fact that ad hoc wireless networks are being deployed distinctively depending upon their particular application; tricky routing issues of different kind are expected in different frameworks.

A routing protocol makes its best effort in order to guarantee positive network performance even in conditions of frequent movement. Hence, its duty could be eased if its designers would be aware of the real situations where the network will be actually utilized in. The problem, that prevents this ideal case, is that it is difficult to get meaningful insights of the particular network applications. In fact, there is currently very little knowledge to generally describe the dynamism of the operating wireless networks.

Having an overview which describes the dynamical changes of the network topology under certain conditions, helps the network designers during their task to take into account all the critical issues involved. A network simulation consists of an attempt to realistically mimic computers network behavior. Its main purpose is to observe and identify the principal features of the network that originate most of the difficulties for the routing protocol.

The simulation approach provides the researcher with many benefits such as repeatable scenarios, isolation of parameters, and exploration of a variety of metrics. Moreover, it permits to set up an artificial, possibly realistic, scenario which may model several conditions. In the case of wireless communication networks, for instance, it will be of particular interest to represent a few conditions such as a sensible Radio Propagation Model (RPM), a representative data traffic model, as well as a reasonable Mobility Model (MM).

Since the conclusions drawn after a simulation study have the target to be useful to the routing algorithms designers; I believe a mobility pattern must make its best effort in order to reproduce real environments. Reproducing real life situations consists of preventing mobile nodes to move freely, and moreover of considering issues related to the radio signals propagation.

So far, there have been several studies that have measured routing protocols' performance in ad hoc networks. Most of these research work have done simple assumptions to neglect a series of real life aspects. Commonly, the researchers have simulated the mobile devices freely moving in flat surfaces; hence, without any regard toward the possible constraints, neither for the motion, nor for the radio signals propagation. Under these hypothesis they were imagining a world where people constantly try to pass through walls, and vehicles suddenly leave the roads to drive into rivers or lakes.

Unlike, in the reality users do not typically move like in a totally random fashion, but rather they like to follow a precise route along a street network. In fact, people on college campuses, cities, and in shopping centers tend to walk or drive their vehicles by following a certain street network to head for precise destination points. Furthermore, wireless channels experience high variability in channel quality due to a series of phenomena. The most significant ones that deserve to be mentioned are multipath fading, atmospheric effects and obstacles such as buildings or mountains. Therefore, depending on the particular terrain of action of the ad hoc network, the radio signals propagation may be affected differently.

My master's thesis work is intended to study the implications of a realistic model on the routing protocol performance. It basically focuses on a fairly realistic city environment artificially set up. The pattern being proposed pinpoints two basic components of fundamental importance: the Mobility Pattern and the Radio Propagation Model (RPM).

The overall structure of the thesis is as follows: Chapter 2 briefly introduces all the terminology and basic concepts, in order for the reader, to gain familiarity with the whole domain. It further presents the problem statement in its concise form. Chapter 3 defines a few criteria the proposed model will be proved against. Chapter 4 presents the most significant previous work already done inherently the concerned subject. All the choices, assumptions, and implementation issues along with a formalization of my own solution, are explained in detail through the Chapter 5. Chapter 6 aims to present the simulation experiments that have been performed. In Chapter 7 the experimental results gathered are shown as a collection of graphs. A part which analyzes the findings, according to the criteria, is included in Chapter 8. Chapter 9 concludes the thesis and gives a few suggestions on possible further future work.

Chapter 2

Mobile Networks

Traditionally communication networks have been static, or nearly static. When electronic devices such as mobile phones, laptops and PDAs became portable, the need to make the computer networks dynamic arouse.

Nowadays, the most electronic devices have wireless access (WLAN or others). Thus, more and more computers are enabled to change their physical location while attached to the network. Hence, the possibility of smoothly changing the point of attachment is provided to the users. However, more and more mobile nodes may also want to communicate either directly with each other or by relying on some relays using the infrastructureless approach commonly well known as ad hoc network.

Several are the occasions in which it is reasonable to have a pure mobile ad hoc network. To cite some applications, among plenty of them, they are employed in situations following a natural catastrophe such as either an earthquake or an inundation. In such situations, it is more than likely that all the normal wired communication infrastructures will be out of service for obvious reasons. Therefore there will be an urgent need, for the rescue crews, to set up a mobile ad-hoc network to replace the damaged ones.

It is undeniable that the networks which involve mobility issues are currently numerous. However, the wired paradigm continues remaining very important for a number of applications. In fact, there are situations in which a network cannot afford to operate with neither low bandwidth nor channel unreliability. For instance, such a scenario may occur when a high flow of data must be transferred under strict time constraints, and with the certainty of succeeding. In this case the wired networks suit better due to their wider bandwidth and higher channel reliability.

2.1 Ad-Hoc Networks

A wireless ad hoc network consists of a set of mobile devices which can communicate with each other by using either the radio channel or infrared. Mobile stations are able to communicate even when moving.

Laptop computers and Personal Digital Assistants (PDA) are an example of possible mobile nodes that can operate exchanging data. An example of a wireless ad hoc network is displayed in Figure 2.1. Mobile ad-hoc networks can be considered as the opposite of the wired Local Area Networks (LAN) which do not usually have any degree of mobility. In between this two completely diverse types of network there are the hybrid ad hoc networks. They consist of networks that include mobile stations as well as wired ones. Usually, mobile nodes outnumber the wired ones but there are no general rules. Figure 2.2 shows an Hybrid network with a point of attachment to the wired world. Several can be the reasons to introduce one or more wired stations, the necessity to have reliable relays in the communication area, as well as the need to have access to a wired domain from the mobile devices.

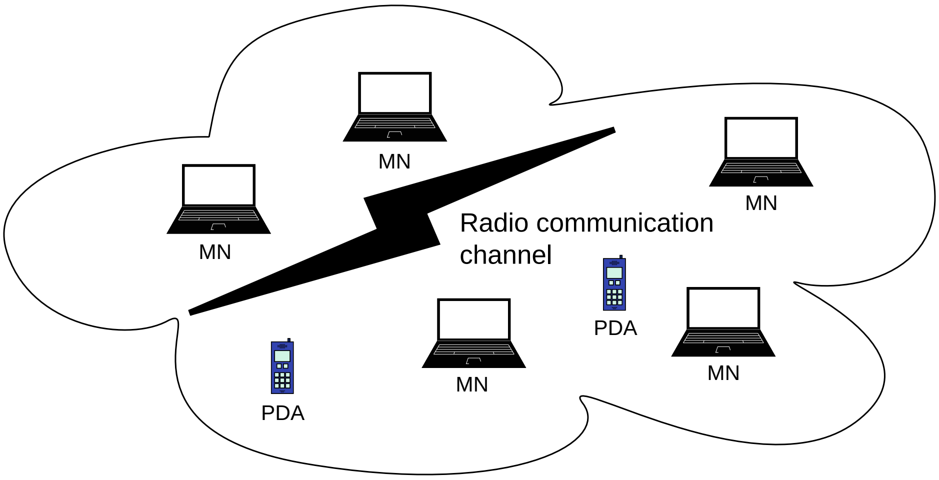

Figure 2.1: A representation of a Wireless LAN.

2.1.1 Hosts vs Routers

A common computer network is typically compound of two diverse set of machines. They are hosts and routers that can be thought of as computers.

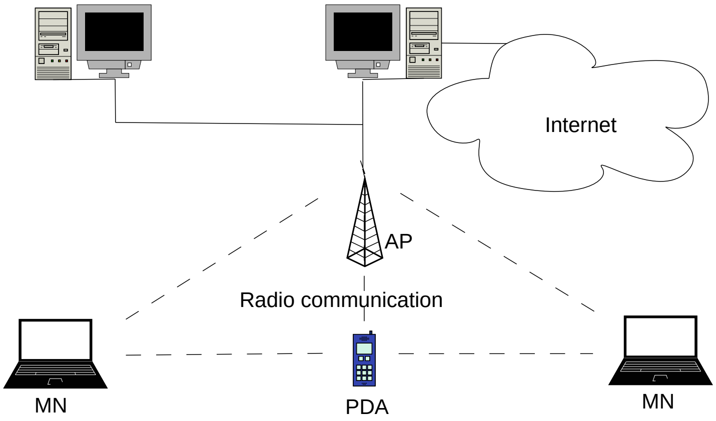

Figure 2.2: A representation of an Hybrid network with a point of attachment to the Internet domain.

The *hosts* are the machines which actually wish to communicate with each other for various purposes. The *routers* are the set of computers which operate to guarantee the communication between the hosts. They perform all the needed operations to send data from a source to a destination. In a wireless ad hoc network, there are not hierarchical differences among all the devices, they are all peers. There is not any device which is particularly in charge of some duty, the nodes can act as host, and at the same time as router as well. Such a mechanism requires all the devices to be provided with all the needed client software applications, but also with the software to actually perform the routing operations (Routing Protocol).

In a wireless ad-hoc network every node is free to join/leave the network whenever it wills. This is a useful feature of the ad-hoc networks but it clearly introduces a series of problems related with the routing issues. Owing to the high mobility degree typically present in these networks, every single peer must collaborate with his neighbors in order to successfully perform a sending operation. Each node, component of the network, must be fair and collaborate forwarding packets heading towards other mobile stations.

2.2 Routing Issues

Hosts in computer networks must face with several issues in order to locate one or more destination hosts. In fact, when a station which belongs to a network wishes to send some information to any other host, it first needs to know where the destination is located and how to reach it. Whenever two nodes are not within each others' proximity, they use multi-hop connections for data exchange. The management of these matters is referred to as routing operation.

A routing protocol is a piece of software of the TCP/IP protocol stack that operates well below the application layer. Simply a routing protocol can be thought of as a computer program that attempts to accomplish its duty as efficiently as possible. It is in charge of setting multi-hop connections up, in order to enable a flow of data between two end points.

Making routing is a duty that is done in many different ways depending upon the network scenario. In fact, wired, mobile or hybrid networks typically force the protocol to address and face with diverse problems. Specifically, there are many different routing protocols; each of them with its own markedly different way of functioning. The scope of this thesis deals solely with protocols for mobile ad hoc networks [7, 22, 31].

In these networks their topology has the tendency to change dynamically, rapidly and in an unpredictable way owing to members mobility. This poses a feature of great challenge to the researchers of the area. For instance, we need to design new routing and transport layer protocols to adapt to the changing topology, to keep the energy consumption low and possibly to maintain high performance. Thus, the routing table management becomes harder to accomplish than in wired networks. Due to the fact that bandwidth is a scarce resource in Mobile Ad hoc Networking (MANET), the number of nodes in a MANET is small compared to the wireline Internet. The scalability issue for wireless multi-hop routing protocols is mostly concerned with excessive routing message overhead caused by the increase of network population and mobility. Routing tables size is also a concern in MANETs because large routing tables imply a large control packet size and hence large link overhead.

2.2.1 Distance Vector vs Link State Routing Protocols

Routing protocols generally use either Distance-Vector (DV) [37] or Link-State (LS) routing [9] algorithms to update and keep consistent the routing tables. In *Distance-Vector* routing DV, a vector containing the cost (e.g., hop distance) and path (next hop) to all the destinations is kept and exchanged at each node. DV protocols are generally known to suffer from slow route convergence and a tendency to create loops in mobile environments. The *Link-State* routing LS algorithm overcomes the problem by maintaining global network topology information at each router through periodical flooding of link information about its neighbors. Mobility entails frequent flooding. Unfortunately, this LS advertisement scheme generates larger routing control overhead than DV.

2.2.2 Flat vs Hierarchical Routing Protocols

A first classification of the routing protocols may be drawn according to the network structure where a protocol has to operate. In fact, different structures affect the design and operation of the routing protocols; they also determine the performance with regard to scalability.

The classification which exists [18] distinguishes between *flat* [7, 22, 30] and *hierarchical* routing protocols. The flat routing approach adopts a flat addressing scheme. This shortly means that each node participating in routing plays an equal role. Moreover, all the routers are able to exchange information with each other in order to fill their tables up with information inherent the whole network topology. In contrast, hierarchical routing usually assigns different roles to network nodes. This approach splits the network up in several regions and then it assigns to the nodes different functionalities inside and outside a region. A router knows the details of its region but not of the other regions. By doing so, both routing table size and update packet size are reduced by including in them only part of the network (instead of the whole). On the other hand, certain path lengths get longer owing to the routes' optimality within single regions.

Typically, as a network grows (beyond certain thresholds), the routing table grows proportionally. Even assuming that terminals are provided with storage resources that can handle the growth, more bandwidth is needed to send link status packets that distribute the information throughout the network. Thus, common flat routing schemes become infeasible because of link overhead. This is a case in which the hierarchical approach better suits. An example, where the hierarchical fashion has been employed is the Internet Hierarchy.

2.2.3 Proactive vs Reactive ad Hoc Routing Protocols

Flat routing protocols in ad hoc networks [24] can be further divided in two (different) categories. Some protocols maintain complete and regularly updated information describing the network topology in every instant [11, 25]. In contrast, others do not keep any complete information but rather they analyze the network only whenever it is necessary earlier than a sending operation.

The former kind of protocol is referred to as *proactive* protocol [31] while the latter one as *reactive* [7, 22]. While a reactive protocol might need some additional overhead to actually discover a path on demand, a proactive protocol is able to retrieve quickly routing information by querying the vast tables kept in memory.

The proactive fashion has the advantage to retrieve rapidly the needed information but it has the disadvantage of needing plenty of storage and communication resources to keep all the routing tables consistent. The reactive fashion has the disadvantage of needing some time to catch a path to follow, and it may overload the channel in case of many synchronous Route Requests flooded, but it has the advantage of not requiring any periodical heavy operation on the channel, allowing the network to be used only for the needed data transfer. In many cases the benefit is worth the trouble. Especially, in mobile ad hoc environment, it is preferable to employ reactive protocols owing to their good performance even in those contests where the mobility degree is extremely high.

Beyond the two types illustrated, there is a third one which mixes the two different fashions to obtain a so called *hybrid* routing fashion [24, 34].

2.3 Dynamic Source Routing Protocol

Dynamic Source Routing (DSR) [23] is a reactive routing protocol which uses the source routing principle to deliver data packets [22]. Headers of data packets carry the sequence of nodes through which the packet must pass. This means that it needs to know the complete hop sequence to the destination beforehand. As in AODV [7], the route acquisition procedure in DSR requests a route by flooding a Route Request packet. A node receiving a Route Request packet searches in its route cache, where all its known routes are stored, for a route to the requested destination. If no route is found, it forwards the Route Request packet further on after having added its own address to the hop sequence stored in the Route Request packet. The Route Request (RR) packet propagates through the network until it reaches either the destination or a node with a route to the destination. Alternatively, a RR can be dropped out if its hop propagation limit exceeds. If a route is found, a Route Reply packet containing the proper hop sequence for reaching the destination is unicasted back to the source node. DSR does not rely on bidirectional links since the Route Reply packet is sent to the source node either according to a route already stored in the route cache of the replying node, or by being piggybacked on a Route Request packet for the source node.

2.4 Protocol Performance

We pointed out in Section 2.2 that ad hoc routing protocols function differently. This leads to observe their diverse capabilities, points of strength and weaknesses. Hence, a particular protocol typically suits better in certain situations than others. Because of this, it is a key factor for the networks designers, to select the protocol which better adapts to the overall system under development or study. In order to know points of strength, weaknesses and peculiarities of every protocol it is necessary to test their performance [14].

2.4.1 Alternative Ways to Evaluate the Performance

Performance evaluation can be accomplished in three alternative ways: analytical/mathematical methods, measurements from an existing system and simulating operations of a model system.

The *mathematical analysis* requires complete and formal specifications of both, the network where the protocol operates, and the protocol itself. Formality is very precise, but it is hardly possible to formalize the ad-hoc network's specifications. The empirical measurement of existing systems, *tracing*, is also an approach which provides accurate and precise information. Unfortunately, it demands a long period or phase of measurements to survey the system in action. Not often a research group has enough resources, budget and time to afford such a pre-study measurement phase. Furthermore, privacy issues, including the confidentiality of certain data may also prohibit the data collection and the distribution of such surveys. It is hence usually preferable to proceed testing protocols performance with the *simulation approach*. Especially, when large number of nodes or various network configurations are evaluated because simulation allows us to vary the environment easily.

2.5 The Simulation Approach

The *simulation approach* provides the researcher with many benefits such as repeatable scenarios, isolation of parameters, and exploration of a variety of metrics. Simulation permits to set up an artificial, possibly realistic, scenario which models several conditions. In the case of wireless communication networks, it will be of particular interest to represent a few conditions such as a sensible Radio Propagation Model (RPM), limited buffer space for the storage of the messages, representative data traffic models as well as movements of the mobile users i.e. Mobility Models.

Shortly, a network simulation consists of an attempt to mimic realistically the computers behavior. Its purpose is to observe and measure some particular parameters that characterize the network system under study. Simulation achieves such a target by emulating potential networks behavior via software. The software is the tool which the researchers utilize and implement to represent and study the different scenarios, and is referred to as simulator.

Many are the simulators available to the MANET community [13, 17, 28, 29, 32]. They are either commercial or open source software shared world wide. Typically, they are all freeware to the academical world. The author decided to perform his research with the help of the Network Simulator 2 [28] (NS2).

2.5.1 Findings' Reliability in a Simulation Study

The researchers performing a network simulation, must be careful to include in the artificial scenario they set up, all the related critical issues in order to draw relevant conclusions afterward. The reliability of a simulation study and of its results can be negatively affected when the simulation does not cover all the critical aspects that it should.

2.6 Radio Propagation Models

Wireless LAN communicate through the radio channel at an assigned frequency band. The radio channel has many various parameters that must be kept into account when signals propagation must be simulated. Some are easy to determine within simulations, like distance between sender and receiver or the utilized frequency. But others must be represented as random functions or constant factors, like interferences or fading effects.

To allow reasonable simulations within an acceptable amount of time, propagation models must simplify the calculations and reduce the required computations to a minimum. The network simulator NS2 [28], offers the implementation of three different Radio Propagation Models (RPMs) to forecast the wireless signal strength.

2.6.1 Radio Propagation Model with Obstacles

All the RPMs that NS2 provides will be presented in detail through Section 5.3. They assume a flat surface where the signals propagate regardless the possible obstacles which can be actually present in the simulation terrain. Basically, these RPMs solely consider the distance between the sender and receiver entities.

In the real world, the presence of obstacles such as mountains or buildings influences the signals propagation through the channel. In most of the cases, obstacles affect the propagation negatively; though, in rare cases fading effect manifests with a positive impact that allows radio signals to be heart even out of the nominal transmission range. This effect is known as *tunnel effect*.

Hence, a precise representation of the the topological properties of the terrain, should be considered when the ad-hoc network simulated is meant to operate in more realistic environments. For this reason, I believe obstacles obstruction is a characteristic that must be included in the Radio Propagation Model.

The RPM that I implemented, to use in the urban environment, considers the buildings as entities that totally block the signals propagation (*Shadowing Obstacles*). Two mobiles can only communicate through the radio channel if no obstacles are within the Line Of Sight (LOS) of the two nodes. Furthermore, the distance between the nodes must be smaller than their radio communication range. From now on, I will refer to this radio propagation model implemented as Radio Propagation Model with Obstacles (RPMO).

2.7 Mobility Models

A *Mobility Model* (MM) can be regarded as the algorithm used to generate all the stations movements within a flat terrain. It is a single simulation parameter, though it actually includes a set of parameters. A mobility pattern specifies the rules which mobile devices will follow during the motion. In particular a model can establish that nodes are moving either on randomly chosen directions (free movement) or according to a well defined street network (constrained movement). A MM can either prevent nodes from standing still or allow pauses during the motion. It usually has a degree of randomness in dictating the motion directives. Currently, there are a number of Mobility Models known in literature [6, 10, 39], and there are many possibilities to customize them in function of the researcher's needs.

The mobility patterns known in literature, create a certain motion which depends on the MM itself. Movements are characterized by their direction, speed, and either a destination point to reach or a duration. When a mobile node concludes its movement the MM decides a new movement to perform for the next period of time. This iteratively continues from the beginning of the simulation until its end, and it is done for every Mobile Node (MN).

Mobility patterns are classified in literature as either *Entity Mobility Models* or *Group Mobility Models* [6]. The former type of patterns have been proposed to independently study the single mobile nodes motion. They dictate devices motion in a manner such that the movement of a MN does not influence in anyhow the behavior of the other peers. On the contrary, the principle employed to create nodes movements in a group mobility fashion makes the nodes move together. The basic idea is to have a so called Master node or an imaginary reference point that freely shuffles across the entire simulation area. The Master logically leads a group of devices. They will move in function of it just by roaming around within a dynamic and narrowest area that surrounds it.

Group Mobility Models come to be very useful whenever the necessity to represent collectivity motion arises. For example, many military scenarios occur when a group of soldiers must collectively search a particular plot of land in order to destroy land mines, capture enemy attackers, or simply work together to accomplish a common goal. Even though this class of mobility patterns is undeniably very important to represent some actual situations, it is not this thesis' target to deal with it. The Section 4.2 will introduce and explain all the details of a few mobility patterns.

2.7.1 Boundless Simulation Area

Commonly, the MMs consider simulation areas which are bounded by their edges. Nevertheless, there exist a possible modification to this common assumption. In fact, in certain situations such as an urban environment, it is undesirable that nodes close to an edge have to pick an opposite direction of movement just to avoid crashing against it. The mentioned modification consists of having a simulation area that does not have any bounds. In this new fashion, a moving mobile which "crashes" against an edge, can continue proceeding in the same direction simply by entering the area from the opposite side (wrap-around border behavior). Moreover, radio signals propagation can pass through the edges. Mobile entities at opposite edges can then communicate.

Many are the algorithms to establish the motion of the mobile nodes. All of them, either directly or indirectly, specify a precise point of the simulation area which a node has to move toward. Given the current position of the node, the path the node will move along depends on the type of the simulation area. For a bounded surface, the path from a point to another along a line will be unique. Unlike, in a boundless surface there will exist always many possibilities of choice. A reasonable decision to make in that case is to choose the shortest available path.

Considering a boundless simulation surface increases the realism of the motion. In fact, in an urban framework it is desirable not to have changes from a direction to its opposite value. This is what we would observe when the edges are constraining the movements. Furthermore, the model provides a uniform spatial distribution of the nodes within the simulation terrain [3].

2.8 Problem Statement

This thesis proposes a new complete and realistic entity mobility model which resembles a boundless urban environment. The aim of this thesis is to study the impact of the shadowing buildings, and of the constrained movements of mobile nodes on the data packets and on the routing operations, in wireless ad hoc networking environments. The mobility model will be first implemented and subsequently tested with a wide set of simulation experiments.

The aim will be accomplished by using the simulation approach. The mobile devices compounding the network are featured with WLAN-radio physical layer, the protocol used at the MAC Link Layer is 802.11 CSMA/CA, the Internet Protocol used at the Network layer is IPv4 and the routing protocol to be investigated is DSR.

Chapter 3

Evaluation Criteria

This section is intended to present the criteria for evaluating the proposed solution. Therefore, it will cover the aspects that characterize the quality of the method proposed. Since I am proposing a simulation method to evaluate a few certain influences, it is fundamental to explain how I will judge and interpret the final results. It is imperative and essential to evaluate a restricted set of suitable quantitative parameters to comprehend the impact that the Urban Model causes. Moreover, these parameters must be intuitive and easy to gather from the simulation experiments run.

3.1 Repeatability and Consistency of the Results

The simulation experiments I will be performing, must be repeatable. I will define how a Movement scenario and a Data traffic pattern, employed in the experiments, must be generated. Hence, I will precisely specify a few fixed parameters such as the range for the speed of movement, the number of CBR S/R pairs, the amount of mobile stations operating in the network, the degree of mobility as well as a few others. Though these parameters will be fixed (they are constraints), the movement scenarios and the traffic patterns generated will be characterized by a uniformly distributed degree of randomness. The fact implies that multiple simulations will have different input data. Nevertheless, they should have a certain similarity owing to the principal fixed parameters mentioned above. This peculiarity must lead to observe equal final results (their tendency) regardless the particular set of input data. This will permit me to get reliable and consistent results to be able to generalize the conclusions drawn.

3.2 Mobility Patterns' Comparison

The overall set of simulation experiments has to be designed in order to point out the principal characteristics of each mobility model. Hence, it must allow me to make a comparison of the three mobility policies used. Diverse patterns will show different findings, I will have to analyze them in comparison with each other to describe each pattern's peculiarities. In function of the particular characterizing features of every model, the results should permit me to observe a few general differences between the distinct models under study.

3.3 Quantitative Parameters

During the simulation experiments, several speeds of movement, and a restricted set of distinct simulation terrains in terms of size will be investigated for each mobility fashion. The final objective is to observe what are the most dominant parameters that govern the routing performance. Main question is whether is the combination of Mobility Model, Radio Propagation Model or rather other input parameters.

Chapter 4

Previous Work

Lately the MANET community has shown a particular interest toward the study of the mobility patterns. In particular, it has been known that the way how mobile devices move in the simulation area affects in a significant manner the happenings in the Network [6, 10, 38]. Due to this observation, the researchers felt the need to design mobility models which closely resemble the typical motion that occurs in real environments. Currently there are two directions of study in mobility modeling: the proposal of new mobility patterns and the analysis of them. The research followed the first direction throughout the 90's [6], to switch in these years the attention toward their analysis [39].

Through this Section we are going to present some significant simulation studies which have dealt with the study of mobility in ad hoc networks. Before starting to discuss those issues we will take the opportunity to provide an overview of the mobility patterns widely discussed in literature.

4.1 Mobility Modeling Approaches

When it comes to model devices' movements in a certain area, many are the key factors to keep into account. Accuracy in describing these factors, helps to simulate closely the reality. In spite of this, often it is excessively tricky to predict the real motion of the mobile nodes, so that some aspects must be discarded or simplified.

The MANET research group, which performed a good few mobility modeling studies [2, 4, 6, 10, 14, 20, 21, 33, 36, 38], suggested two basic approaches to obtain mobility modeling. A first way is by *Synthetically* obtain a set of formal rules which strictly describe how the motion must be generated. In this way a mobility pattern consists of a set of rules according to which each mobile node has to move. A very trivial example would be obtained by defining that the direction must be strictly horizontal, the speed constant, and no pauses are allowed. Basically, the many existing synthetic models consist of something sophisticate compared to this trivial example. Another approach is to observe existent systems and subsequently set up an artificial scenario of movements that is based on the observations done in the field, *traces*. If we can trace mobile hosts in their real world, we can gain valuable insight to model actual motion. Unfortunately, for the same reasons mentioned in Section 2.4.1, tracing is in general not an affordable direction to follow in the MANET world.

In contrast, the study of wired LANs or of cellular phone networks can currently take advantage of a few trace studies that have been carried [26]. The fact that no traces are available yet for ad-hoc systems, is certainly due to the rather new technology. Moreover, an additional cause is that movement tracing would require a precise recording system for the locations of the Mobile Stations (MSs). The Global Positioning System (GPS) is for instance a good suitable choice. In the cellular networks, even a positioning system with a lower degree of precision suits to achieve the aim. This is because in the Global System for Mobile communications (GSM) world it is enough to know which cell a cellular phone belongs to. This differentiation comes from the quite different technology that characterize the GSM terminals. In fact, the average cell radius it is in the order of several hundred meters or even kilometers; that is quite wider compared with the ad-hoc devices.

4.2 Synthetic Mobility Models

In Section 2.7 I provided a commonly used classification for the Synthetic MMs. Synthetic mobility patterns could further be classified according to a very good distinction presented in [39]. They have proposed to classify Synthetic patterns as either *Constrained Topology Based* [21] or *Statistical models*. According to the cited grouping, in the first category they include those MMs which simulate real world scenarios, but still have some randomness to provide for variability. It is this group which patterns mimicking freeway scenarios [2, 14] belong to. Likewise, the mobility model proposed in this master's thesis is evidently a Constrained Topology Based model. Unlike, common models as Random Waypoint (RWP), Random Direction (RD), and Random Walk (RW) belong to the purely statistical models category. In fact, hosts can move to any destination and their velocities and directions are randomly chosen. It is therefore evident that such models are basically idealistic, rather than realistic.

In the opinion of the author the mentioned classification fits very well when realistic mobility management has to be discussed. Hence, this section introduces and presents some Synthetic mobility models grouped as discussed above.

4.2.1 Statistical Models Overview

Statistical MMs describe the behavior of a set of entities that move within a specified area in an unpredictable manner. Their name comes from the high degree of randomness which characterizes them.

Random Walk Mobility Model

Random Walk (RW) [6] is a very simple entity mobility model. It makes nodes moving by randomly choosing a direction of movement between $[0, 2\pi]$ and a speed in $[Speed_{min}, Speed_{max}]$. Subsequently, the duration d, of every movement, can be established either by fixing it or by fixing the length of the movement. The two ways are alternative. In this model, when a MN reaches the bounds of the surface it "bounces" off the simulation border with an angle determined by the incoming direction. Finally, immediately after that a time d has gone by, the node has reached its destination and it resumes the movement with a new speed and direction.

The pattern makes random decisions, both speed and direction are chosen accordingly to a uniform distribution. The model does not have memory, meaning that it does not make decisions based on previous movements. This pattern is very simple but at the same time also unrealistic. In fact, it produces very sharp and sudden turns.

Probabilistic Random Walk Mobility Model

Chiang's MM [8] is a variation of the more common Random Walk. This extension of the earlier mentioned Random Walk introduces the probabilities of forward and backward movements for each coordinate. In its particular implementation the model is two dimensional. Although, it can easily be extended to its respective N-Dimensional (ND) version for whatever positive N.

Probabilistic Random Walk (PRW), utilizes a probability matrix to determine the position of a particular MN in the next time step. In particular, it makes decisions based on a matrix of probabilities P (4.1), that specifies how probable are the events of not moving (0), moving a step backward (1) or moving a step forward (2). The length of the steps s is a constant. The whole MM is represented by a state chart along with a matrix of probabilities for every of the coordinates x, y. The matrix P is as follows:

$$P = \begin{bmatrix} P(0,0) & P(0,1) & P(0,2) \\ P(1,0) & P(1,1) & P(1,2) \\ P(2,0) & P(2,1) & P(2,2) \end{bmatrix} \tag{4.1}$$

where each non zero probability represents a transition in the state chart shown in Figure 4.1.

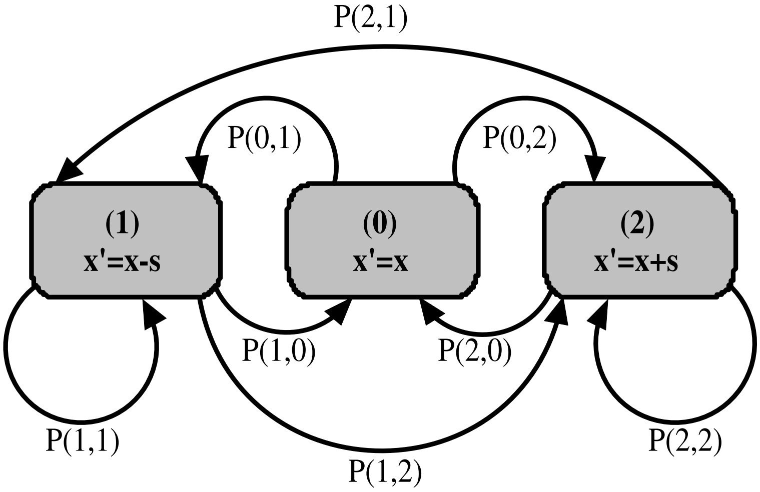

Figure 4.1: A representation for Probabilistic Random Walk via State Chart.

In [8] the matrices' values were specified as shown below:

$$P_x = P_y = \begin{bmatrix} 0 & 0.5 & 0.5 \\ 0.3 & 0.7 & 0 \\ 0.3 & 0 & 0.7 \end{bmatrix} \tag{4.2}$$

The probability matrices P_x and P_y allow a MN to move in any direction as long as it does not return to its previous position. Though, this particular sequence of happenings can be obtained by introducing a pause time in the current location. *Chiang's* MM belongs to the statistic group. Nevertheless, it produces probabilistic rather than purely random motion. For example, as people complete their daily tasks, they tend to continue moving in a semi-constant forward or backward direction. Rarely we suddenly turn around to retrace our steps, and we never take random steps hoping that we may eventually wind up to somewhere relevant to our interest.

This way of representing the variation of the x, y coordinates is very intuitive and it may be applied to represent also other mobility patterns. In particular, in Section 5.1.1 I will describe my own city mobility model by using a similar approach by state chart. It is a good notation since I want to represent certain features such as probabilities of turning and size of the steps. When a probabilistic approach is deemed to be relevant enough to be used, it is always complicated to choose probabilities that truly describe the model we want to be mimicking.

Random Waypoint Mobility Model

Random Waypoint (RWP) [6, 38] is basically an enhancement of the previously described Random Walk. Like in Random Walk, a node must choose a speed between $[Min_{velocity}, Max_{velocity}]$ which is uniformly distributed. Instead of choosing a direction it chooses a destination point to travel towards. In this model a node is allowed to stand still in certain points of the surface before resuming the motion. The pause time is established according to a uniform distribution between $[P_{min}, P_{max}]$. This is the principal difference with Random Walk which also leads to have nodes that can start at different instants of time.

The pattern is more realistic compared with random walk because of the pause times. Though, there is no high degree of reality. The most argued issue which makes the model be deemed as idealistic, is the fact that MSs tend to continue moving in the central part of the area and only rarely they approach the borders [38]. This phenomenon is often referred to as *density wave*. An additional problem is the disposition of the MNs at the beginning of the simulation. In fact, even though the mobiles are randomly distributed, their initial disposition is not representative of the manner they distribute when moving [6].

The concerned model is the most spread in the simulation studies performed so far in ad-hoc environments [6, 10, 25].

Random Direction Mobility Model

In this mobility model a node chooses its initial direction and speed in a fashion similar to random walk [6]. It subsequently continues traveling until it "crashes" against the boundary. At this point it stops for a specified time before resuming the movement again with a new direction between $[0, \pi]$ and a speed in $[Speed_{min}, Speed_{max}]$.

This simple model has been proposed with the aim to eliminate the tendency of the RWP and RW models to mostly move on the center of the area. The problem is overcome, but it is more likely to have the network partitioned, that implies a decrease in protocol performance. A very important parameter is the pause time chosen when the border is reached. Different choices will lead to draw different conclusions.

Such a model is unrealistic since it is unlike for people to spread themselves evenly throughout an area and pause only at the edge of this given area.

Boundless Simulation Area

In order to eliminate the impacts of simulation-edge effects [3, 4], the *Boundless Simulation Area MM* was proposed [6] that allows nodes to travel unobstructed in the simulation surface. The topology is neither rectangular nor square. In fact, the area of movement is the internal surface of a 3D *Torus-Shaped* solid. An easier way to imagine this complicated geometric solid is by thinking of it as either a square or a rectangle with the constraint that mobile nodes disappear on the top to reappear on the bottom and viceversa (likewise it happens for left-right). A representation of the situation is depicted in Figure 4.2.

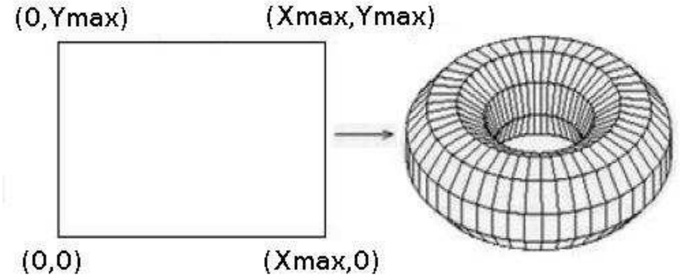

Figure 4.2: A Torus-shaped terrain.

An undesired side effect of such a model [15] is that a static node, and a node moving in the same direction for a wide enough time interval become neighbors repetitively. This is certainly an implication to take into account when modeling hybrid networks. In fact, this is the case in which there will exist both static, fixed hosts and mobile devices. Thus, in order to alleviate this drawback, the torus size should be large enough in proportion with the radio communication range of the mobile entities.

4.2.2 Constrained Topology Based Models Overview

Often, entities do not move in an unpredictable way. *Constrained topology based models* attempt to describe this fact. Their nature is characterized by a wide set of constraints to keep into account. Below I analyze in detail the most significant Constrained MMs previously proposed in literature that are relevant for this thesis.

City Section Mobility Model

The *City Section* MM [26] aims to represent a limited section of a city. MNs move with the objective to reach a certain point of interest. The destination is reached keeping into account the numerous restrictions which the model imposes. In turn, it includes a street network and a set of points of interest. In addition, it could include safe driving characteristics such as speed limit, minimum distance allowed between pairs of nodes. Furthermore, a high speed road along the perimeter of the simulation area would be a realistic way to model the situation. In order to eliminate the restriction of solely representing a limited part of the city, a boundless topology can be introduced.

This model, if fully implemented, it certainly represents a realistic urban environment with its many actual constraints. On the other hand it is tricky to succeed in implementing all its factors. This thesis presents one possible implementation of it.

Obstacle Mobility Model

The *Obstacle Mobility Model* [20] focuses on a series of points which make the situation being modeled rather realistic. People move toward certain points of interest and there are obstacles as in the real-life world. These obstacles are polygon shaped and they block people's movements as well as hinder signals propagation. Finally, people do not walk along random trajectories; they usually follow existent pathways to get to their point of interest.

Take campus scenario as an example. Buildings are modeled by placing rectangles of random size at random locations; Pathways are built by Voronoi diagram of the vertexes of these rectangles. Doorways are the intersection of these pathways with the buildings. A *Voronoi* diagram [12] is a partitioning of a plane with n points (target locations)into n convex polygons such that each polygon contains exactly one point and every point in a given polygon is closer to any other. A MN chooses a building to head for, it moves and when on the desired destination it stops for a certain pause time.

Sparse Shadowing Blocks in the simulation surface make the routing protocol's duty harder than in the other more common MMs. Typical radio communication model [14] do permit MNs to communicate only if in Line-Of-Sight with each other. Likewise, communication is allowed only either Indoor or Outdoor. Since Blocks are totally hindering the radio waves, it is not possible that one MN which is indoor, can successfully communicate with other terminals that are located either outdoor or internally in a different block.

Reference Point Group Mobility Model

Reference Point Group Mobility Model (RPGM) is a group MM [2]. A group of MSs want to move together to accomplish a common goal. The MNs motion is strongly characterized by the movement of the group's logical center. The group logical center is assigned a new position at regular intervals of time. Subsequently, the Reference points' (RPs) location is updated accordingly. Finally, MNs locations are computed based on a Group Motion $\underline{GM}$ and a Random Motion $\underline{RM}$ vectors.

> $\underline{GM}$ can be EITHER predefined OR randomly chosen.
>
> $\underline{RM}$ is randomly chosen. The direction is uniformly distributed in $[0, 2\pi]$, the length is uniformly distributed as well in $[L_{min}, L_{max}]$, with a radius centered at the Reference point's location.

RPGM is particularly suited to represent movements of an avalanche rescue crew (Humans and Dogs). Many possible implementations can lead to obtain very diverse Group motions.

4.3 Simulation Studies Based on Random Waypoint MM

Random waypoint MM is surely the most commonly used in protocol performance evaluation studies. This paragraph provides an idea of a few previous simulation studies done using RWP-MM.

In [5] they have evaluated the performance of a few routing protocols. This simulation study has tested the performance of DSDV, TORA, DSR and AODV when operating under the same conditions. In this work they provided a ranked list of the protocols mentioned, obtained by evaluating certain particular performance metrics. In [19] RWP-MM has been employed to evaluate the goodness of a few possible routing metrics. *Y. Han et al.* [16] used the RWP pattern to develop an approximate model for computing the distribution of link duration.

Random Waypoint MM represents a situation that is far from realism. The mobility model concerned is very simple and this is certainly one of the main reasons that makes researchers preferring it over the others. Though, its simplicity should not be enough to justify its employment in numerous researches. In fact, the mobility pattern has several peculiarities and undesired side-effects that will be pointed out in Section 4.3.1.

4.3.1 Limitations of Random Waypoint MM

In most cases, the probability distribution of the initial locations and speeds of the nodes differ from the distribution at later points of the simulation. This is an undesired side-effect since nodes' location and their speeds do influence the protocols performance. *T. Camp et al.* [6] noticed the problem and proposed a simple solution that may be applied. The proposal was to discard an initial part of the simulation with the hope that values obtained after the transitory phase are more reliable. *W. Navidi et al.* [27] have criticized this solution. In fact, there are two potential drawbacks. Firstly, the approach introduces an inefficiency caused by the discarding of data. Secondly, it is nearly impossible to correctly predict how long must this transitory initial phase be lasting. According to the author's intuition, this initial transient time could be minimized by having nodes moving at unreasonable high speeds for a very short period, before setting it at the desired value. In fact, it appears which nodes must travel for a long enough distance before they dispose in a stable manner.

In addition, it has been observed in [38] that the model fails to provide a steady state, since the average nodal speed consistently decreases over time. They have noticed that the speed decay is not due in anyhow to the pause time, but rather directly to the speed distribution itself. The simple solution they proposed is to choose a minimum, non-zero speed.

Yet another side-effect, produced by the RWP Mobility Model, is that nodes tend to move crossing the central part of the simulation area [6, 27, 38]. The effect obtained is that they are either all concentrated in the center or all dispersed nearby the edges. The nodes converge, disperse and then converge again. This obviously markedly changes the protocol performance and nodes distribution. A possibility to avoid this dis-uniform spatial distribution, is to utilize a boundless simulation plane.

4.3.2 An Enhancement for Random Waypoint

An interesting Mobility Model (MM) which improves the RWP, was proposed proposed by *Bettstetter et al.* in [4]. The idea is to have a certain smooth movement in both direction changes and speed variations.

There are two independent processes that dictate in which instant of time a node must vary its speed or direction. The processes specify when either a speed or direction change event occurs. When an event of changing v or d occurs, either a Speed or a Direction target to achieve are chosen respectively between $[Speed_{min}, Speed_{max}]$ and $[0, 2\pi]$. Subsequently, the smooth change for the concerned parameter starts. The Speed is varied according to a uniformly distributed acceleration in $[A_{min}, A_{max}]$. The direction is gradually varied according to a fixed duration of the curve d_c. In particular, given the difference between the current and target directions along with d_c, it is computed how the direction must vary over the time. Speed and Direction smoothly vary until either they reach the target value or until a new event imposes a new variation.

An additional mechanism allows to distribute the velocities according to a non uniform probability distribution. The mentioned mechanism permits to have a set of preferable values such as $Pref_{speed_1}, Pref_{speed_2}, ..., Pref_{speed_m}$ to make the entities moving more often with suitable realistic velocity. Likewise, it happens for the acceleration distribution. Thanks to this peculiarity it is possible to model situations where there are nodes that typically move differently. For instance, we can realistically deem the presence of different classes of users such as pedestrians, and taxi-driver etc.

The presented model, is still a sort of RWP but it is not memory-less and it reasonably changes the motion parameters. The fact of having two independent processes permits to eliminate synchronized changes for speed and direction. In fact, these two important parameters that fully describe the motion, were varied always at the same time when using RWP. Furthermore, with the pattern concerned they succeeded to eliminate the pitfall of sharp and sudden turns present in RWP.

4.4 Other more Realistic MMs

There are a variety of environments where the deployment of ad-hoc networks is expected. A sampling of these includes cities, campuses, highways, conferences and battlefields. What most of those have in common is the presence of blocks to hinder the radio signals propagation along with the limitations of movement over certain streets. In the previous sections, we have analyzed a few mobility patterns that do not model the just cited actual situations. This section provides the reader with additional Realistic MMs that have been previously implemented.

4.4.1 Streets Constrained MM

In [2] they have made a study to compare the routing protocols performance in ad hoc environments. They utilized a few of the commonly used MMs. Additionally, they employed two diverse mobility models in which the movements were constrained by a network of streets that mobile devices were forced to walk along. Specifically, they wanted to design MMs that had both spatial and temporal dependency. From their point of view a MM should not be completely memory-less; meaning that every decision made should depend on the history of the previous ones.

First, they designed a MM *Freeway*, useful to track vehicles on a freeway. In their assumptions each mobile entity is restricted to move within its lane, the velocity is temporally dependent on its previous value and two mobiles within the same lane must stay separated by a distance exceeding a fixed Safety Distance (SD). Second, they tested Protocols Performance using a Manhattan like mobility model. It consists of a MM in which the nodes move by following a grid of Vertical and Horizontal streets. The model closely resembles an urban environment where the mobiles at a crossing point decide how to continue the movement. They will decide with fixed probabilities whether turn left or right or rather go on straight. Moreover, they introduced a mechanism to have the current speed based on its previous value. Their findings show how drastically the MM can affect the protocols performance.

This proposed pattern to study urban frameworks is valuable, but it is lacking the ratio constraints that typically exist in such a situation. In fact, none obstacle has been located in the urban environment. Hence the model is still rather idealistic.

4.4.2 Scenario-Based MMs

Johansson et al. in [21], made a research to investigate the effects of less artificial movement scenario on the protocol performance. The investigation has gone through three particular fairly reasonable situations. Their study has modeled indoor and outdoor situations such as *Conference*, *Event Coverage* and *Disaster Area*. They introduced movements restrictions to make entities moving only according to strict rules. For instance, the Conference scenario has a speaker moving in a small area close to a border and many people following its presentation. The people move a lot close to the entrance, and only seldom from a potential armchair toward the exit. Furthermore, each of the proposed indoor situation was characterized by a set of small building blocks (actually walls) to totally hinder the radio signals.

Surprisingly, they have concluded that those realistic frameworks they analyzed, did not significantly change the protocol performance compared with the common RWP-MM. The explanation they gave is that in their environments the mobility degree was very low. In fact, they had rare movements, slow motion and few obstacles. This allowed the protocols to have a similar behavior in RWP and realistic scenarios. Additionally, they also pointed out that in whatever situation they have tested, ad-hoc reactive routing protocols had the edge on the proactive ones.

4.4.3 A Realistic Simulation in a Campus

In Section 4.3.2 I mentioned a manner to model mobility which deems a few real-world issues, but it does not consider neither a street network nor a set of obstructing blocks. Section 4.4.1 introduces path constraints for the mobiles and Section 4.4.2 proposed the modeling of shadowing walls.

Jardosh et al. [20] join the limitations of a street network with those provided by shadowing buildings, to set up an artificial framework that resembles a university campus. They came out with the implementation of an obstacle mobility pattern which has many input parameters, and particularly a set of blocks to locate in the simulation terrain. Based on the input, the model draws the possible paths to obtain a Voronoi diagram (Section 4.2.2). In their particular implementation, the buildings function as obscuring barriers for the wireless signals. Their experiments have tested the model by providing as input the set of buildings which they have in their university campus.

One observation they provided, is that the street network depicted by the Voronoi algorithm, closely resembles the one they actually have. They have got some measurements to investigate the performance of AODV. Their findings, show that the blocks strongly affect the data delivery ratio. This has been explained by an high failure of route discovery attempts. Another surprisingly finding they have found, is that the control overhead was observed to be lower when the obstacles were considered vs. the same simulation terrain solely with streets. They believe this is directly related with the low delivery ratio. In fact, they said, many data sessions must be aborted beforehand due to the impossibility of the communication. This eases the routing protocol duty to maintain routes never found. Here the apparently good thing is that routing overhead is low, but the problem is that data are never delivered.

4.5 Summary

When evaluating the influences of mobility on the network performance, it is a key factor to set up adequately the artificial scenario. Therefore, often obstacles and streets must be included in the mobility pattern. A good role would also be to employ models that have memory to make decisions based on the past history of the happenings.

4.6 Influences of Mobility Models on Routing Protocols

Many Applications of mobile ad-hoc networks are expected to operate in a highly dynamic environment with high nodes mobility. Moreover, the topology in which devices move is characterized by the various constraints that typically exist in actual situations. Network performance thus, depends on how well the routing protocol employed adapts to the dynamics.

To evaluate routing protocols performance, it is inadequate to use only one mobility pattern. Various models that spam across a wide set of mobility characteristics are needed. In particular, evaluating a single protocol must be done by running simulation experiments over different MMs to see how its performance changes. In contrast, when evaluating a group of protocols they must be run in a single MM to be able to rank each of them according to their performance.

Chapter 5

Modeling Urban Mobility

Wireless networks are characterized by a wide set of parameters that must be realistically modeled when setting up artificial scenarios. The scenario which I aim to represent is an urban environment where typically ad-hoc networks are expected to operate. I assume that the urban environment provides a pervasive computing service between portable devices. In this case the mobility pattern and the radio propagation model are certainly two significant factors to study.

This thesis proposes, implements and tests a new complete and realistic entity mobility model. It is basically an enhancement to the common Manhattan MM. It is realistic in a sense that it dictates the nodes motion across a set of pathways, it includes a set of obstructing obstacles, and it considers a boundless surface.

5.1 The Urban Mobility Model

Commonly, a mobility pattern dictates the motion directives without forcing the entities to walk along some pathways. Clearly, this assumption is a simplification that allows to ease the generation of the nodes' movement within a certain area. On the other hand, it leads the researchers to judge very unrealistic situations.

To avoid unpleasant drawbacks of any kind, I decided to model a city-like environment which includes a series of constraints. Therefore, I modeled the entities' motion to be restricted by a network of streets. In particular, it consists of a flat grid compound of vertical and horizontal lines. They are functioning as bidirectional lanes. Horizontal and vertical streets are parallel and equidistant from each other as illustrated in Figure 5.1. The intersection points of the streets form a set of *crossing points*. The Figure also displays a set of square buildings to prevent the radio signals propagation.

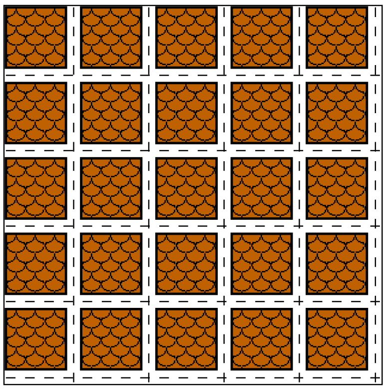

Figure 5.1: An example of an urban environment.

The map, and its grid are uniquely depending on the parameters reported in Table 5.1.

Table 5.1: The map parameters.

Parameter	*Referred to as*
Number of Horizontal streets	N_h
Number of Vertical streets	N_v
city section Width	w
city section Height	h
set of Buildings	$B = \{b_1, ..., b_m\}$

I define a set of Buildings B to be a set of rectangles with their basis parallel to the X axis[1]. Formally, we define a building $b_{\overline{v}_1,\overline{v}_2}$ as the rectangle $R_{\overline{v}_1,\overline{v}_2}$ with its left bottom vertex $\overline{v}_1 = (x1, y1)$ and its right top vertex $\overline{v}_2 = (x2, y2)$. Where the vertexes' coordinates must be such that $(x1 < x2) \bigwedge (y1 < y2)$.

An additional point of strength of the mobility model being proposed is the possibility for both MNs and radio signals to pass through the edges which delimit the simulation terrain. This additional feature has been introduced to

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[1] Buildings more complicated in shape can be modeled by locating rectangles close to each other.

be able to mimic a real city where is desirable not to have a strict delimiting perimeter. In this way users who reach a bound can freely pass through it, and proceed their route without being obligated to suddenly invert their steps. This possibility allows to simulate cities arbitrarily big in size without introducing any heavy computation during the simulation.

5.1.1 The Motion

Nodes always start from a crossing point of the streets, their initial location is randomly chosen in $\{P_1, P_2, ..., P_m\}$; where P_i is a generic crossing point formed by the roads, and where the probability distribution is uniform. Their time of departure is established according to a uniform distribution between $[T_{min}, T_{max}]$ and it is expected to be different for each MN. Once that MNs are disposed in the area, an iterative process begins to determine separately the nodes motion. The algorithm firstly chooses a speed in a uniform distribution between $[Speed_{min}, Speed_{max}]$. Lastly, it decides either a point of interest[2] to travel toward or a pause time. The node being deemed will head for the point with the chosen velocity. The possible points of interest to be picked are always three, those adjacent to the current location, excluding the point where the node came from. The probabilities of not moving, going straight, turning left and turning right can be respectively set as $\{P_p, P_s, P_l, P_r\}$. Furthermore, whenever a node does not move, the pause time has to be uniformly chosen between $[P_{min}, P_{max}]$.

It is important to observe that this motion model does not consider the case of making a step backward to the point where a node came from. This is somehow realistic since, most of the times, people do not suddenly invert their route to go exactly a step backward and then forward again. Initially, and when a possible pause time interval runs out, MNs randomly select out of all the four possible directions with an equal probability.

The algorithm that automatically generates the Mobile Nodes (MNs) movement can be described via the state chart depicted in Figure 5.2. The state chart has five different states that respectively stand for: no movement (0), horizontal step backward (1), horizontal step forward (2), vertical step forward (3), and vertical step backward (4). Observe that the state (0) is also the initial state. The size of the horizontal and vertical steps $H_s = \frac{w}{N_v}, V_s = \frac{h}{N_h}$

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[2] A *Point of interest* is always a crossing point.

are function of the map's parameters[3]. The decrement/increment of the x and y coordinates, internally reported in the states, are obtained as an operation mod *width* for x and mod *height* for y. Every transition in the state chart occurs in the simulation with the probability specified on the arcs. In the figure, the ingoing transitions to (0) imply a pause time. Note that two pauses in a row are not permitted. From now on, we will refer to the proposed pattern as *Urban Mobility Model* (UMM).

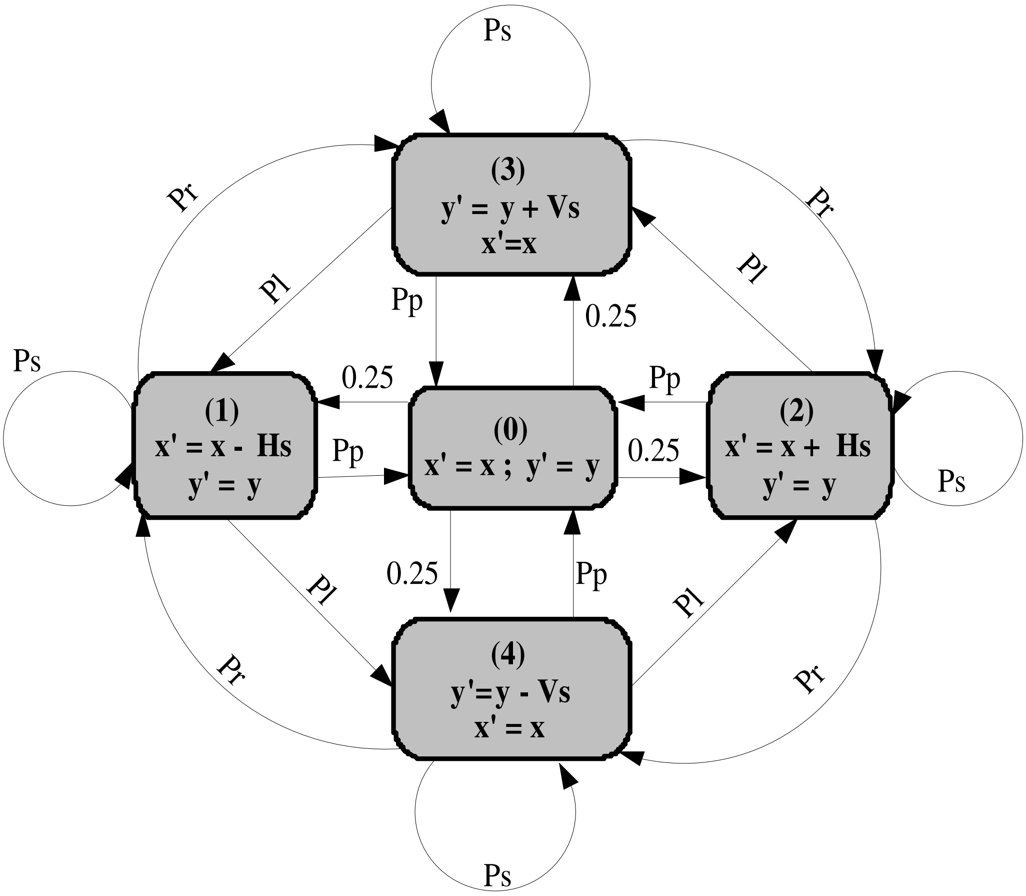

Figure 5.2: The state chart describing the motion of UMM.

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[3] Note that a map was previously defined by specifying the number of streets N_h and N_v along with its size. Alternatively, it could have been defined by the steps' size H_s and V_s, along with either the number of streets or its size w, h.

5.2 The Torus Terrain

As already mentioned, to significantly represent an urban environment it is opportune and desirable to model a boundless area (Sections 2.7.1, and 4.2.1). The city scenario should adapt large cities with regular ground plans. This is a feature that is not built-in with the current version of the Network Simulator 2. Hence, I implemented an extension to the network simulator that integrate it.

A torus surface introduces relevant effects on the mobility model being used. In fact, nodes moving from a current location to a target location always can choose between several possible paths along a line. There are always four alternative paths available. This does not happen when the surface is delimited by non passable edges. In my implementation, a node always selects the shortest line joining the current location and the destination point as path to follow. An additional module guarantees that nodes select only crossing points as target location. The result is that nodes are constrained to move along the city roads with a wrap-around border behavior.

The algorithm to compute the direction of the shortest line joining two points in the torus surface is formalized by the Equation 5.1. Given the current position vector of a mobile as $\overline{p}_c = (x_c, y_c)$, and the coordinates of a destination point that the node wants to reach as $\overline{p}_d = (x_d, y_d)$ the direction $\overline{dir}$ of the shortest line is:

$$\overline{dir} = (x, y) \tag{5.1}$$

Where:

- $x = \begin{cases} x_d - x_c & if\ |x_d - x_c| \leq \frac{x_{max}}{2} \\ x_{max} - |x_d - x_c| & if\ (|x_d - x_c| > \frac{x_{max}}{2}) \bigwedge (x_c > x_d) \\ |x_d - x_c| - x_{max} & if\ (|x_d - x_c| > \frac{x_{max}}{2}) \bigwedge (x_c < x_d) \end{cases}$
- $y = \begin{cases} y_d - y_c & if\ |y_d - y_c| \leq \frac{y_{max}}{2} \\ y_{max} - |y_d - y_c| & if\ (|y_d - y_c| > \frac{y_{max}}{2}) \bigwedge (y_c > y_d) \\ |y_d - y_c| - y_{max} & if\ (|y_d - y_c| > \frac{y_{max}}{2}) \bigwedge (y_c < y_d) \end{cases}$

Likewise, keeping into account the algorithm just presented, it follows an unusual way to compute the distance between two nodes. The fact is of fundamental importance since it affects the signals propagation. Equation 5.2 formalizes the algorithm to calculate the distance d between two mobiles respectively located at (x_1, y_1) and (x_2, y_2) used when a torus surface is being deemed.

$$d = \sqrt{[min(|x_1 - x_2|, x_{max} - |x_1 - x_2|)]^2 + [min(|y_1 - y_2|, y_{max} - |y_1 - y_2|)]^2} \tag{5.2}$$

where x_{max} and y_{max} are respectively the width and height of the rectangle which has been "rolled" to obtain a Torus.

5.3 Modeling Signals Propagation

The underlying channel model in ns-2 is quite simple [1]. The simulator calculates the receiving power Pw_r for every transmission between two nodes with the chosen propagation model. Once Pw_r has been computed, the simulator distinguishes between three diverse cases.

In case Pw_r is greater than a receiving threshold RX_{Thresh} the signal is assumed to have enough power to permit proper reception at the receiver side. This signal will certainly interfere with other transmissions being performed. If Pw_r is below RX_{Thresh}, but greater than the carrier sense threshold CS_{Thresh} the receiver node must drop the packet. Though, the reception power still interferes with other signals. Transmissions with receiving power Pw_r smaller than CS_{Thresh} do not even disturb other simultaneous transmissions at the same node. This is a simple assumption of the radio propagation model internally implemented into the network simulator. In fact in the real life, one transmitter itself may not disturb a node if $Pw_r < CS_{Thresh}$, but several weak signals of this kind simultaneously received at the same node, may constructively originate a stronger interfering signal.

The receiving power is differently calculated depending on the propagation model. Moreover, in each possible model the receiving power must always be set to zero whenever the two entities communicating are separated by more than the Transmission range R. This forms a circular coverage area around a sending node and a sharp range limit.

5.3.1 Free Space

The *Free Space* model (FS) only assumes the direct path between transmitter t and receiver r. Certainly the receiving power is depending on the transmitted power P_t. Other parameters which are involved to compute Pw_r

are: the wavelength λ, the gain of the transmitting and receiving antenna (G_t, G_r), the distance d between the two communicating nodes and an introduced system loss coefficient L. The only parameter which is not system wide constant is the distance between sender and receiver. Furthermore, the receiving and the carrier sense thresholds are kept constant throughout the simulation. Equation 5.3 shows the particular algorithm used in the Free Space model.

$$Pw_{r-FS}(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L} \tag{5.3}$$

The free space model, is very trivial and hence it eases the simulation overhead for forecasting the signal power at the receiver side. Such a radio model is not considering any issue related with neither fading nor ground reflection.

5.3.2 Two Ray Ground

The *Two Ray Ground* (TRG) is a model that improves the principle of functioning of Free Space. Again, the only real variable parameter is the nodes distance d. Two additional system constraint parameters are introduced in the formula. Specifically, h_t and h_r are the heights of the antennas. The signals propagation model concerned, keeps into account both the direct path between S/R and the ground reflection path.

Hence, the additional feature of the TRG is that ground reflection negatively affects the receiving power due to the multipath effect. For nodes within a certain threshold distance $d_{thresh} = 4\pi h_t h_r/\lambda$, the model behaves as the free space (no ground reflection is considered). In contrast, when nodes are far apart from each other for more than this threshold distance, then the receiving signal strength is inverse proportional to d^4. Evidently, this restriction strongly affects the power of a signal when the distance is relevant. The assumption makes the power prediction to be more realistically resembling the real world situations. Specifically, the formalization of TRG resides in the Equation 5.4. Observe that for each d over the threshold $\frac{d_{thresh}}{d} < 1$.

$$Pw_{r-TRG}(d) = \begin{cases} Pw_{r-FS}(d) & d < d_{thresh} \\ Pw_{r-FS}(d)(\frac{d_{thresh}}{d})^2 & d \geq d_{thresh} \end{cases} \tag{5.4}$$

Over short proximities two-ray-ground itself does not give a good result due to the oscillation caused by the constructive and destructive combination of the two rays. Hence, the choice of still utilizing the Free Space model in such a situation is justified. In Figure 5.3 is depicted the receiving power forecasted by FS and TRG radio propagation models ($d_{thresh} = 86mt$).

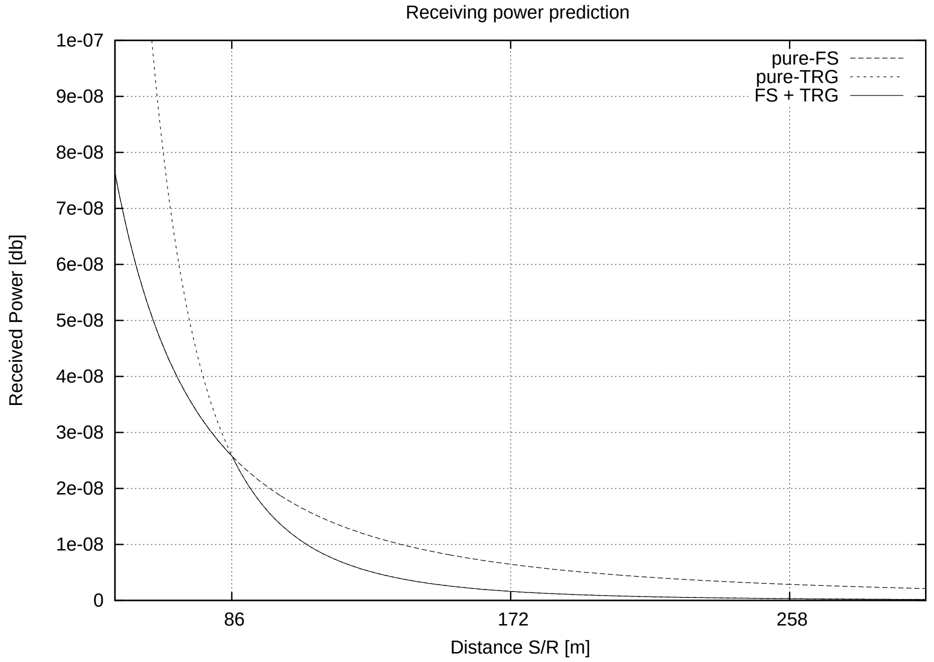

Figure 5.3: The received power forecasted by FS and TRG propagation models.

5.3.3 Radio Propagation Model with Obstacles

The objective of my study is to observe how shadowing obstacles in the simulation terrain affect the protocol performance. Unfortunately, the Network simulator 2 [28] does not provide any RPM that allows to handle this important factor. For this reason I implemented myself, a simple Radio Propagation Model which includes this feature.

Radio Propagation Model with Obstacles (RPMO), is an improvement of the two ray ground model which handles signals propagation in a more severe manner. In fact in my implementation, a simulation area can contain a set of obstacles $O = \{obs_1, ..., obs_m\}$ of whatever shape that totally hinder signals propagation (see Figure 5.1). This feature causes nodes not to have a circular coverage range when close to a block. In such a case there exist a cone shaped part of the normal circular coverage range that is an area of dark. Specifically, an *area of dark* is a surface where the radio signals cannot propagate due to the blocks obstruction.

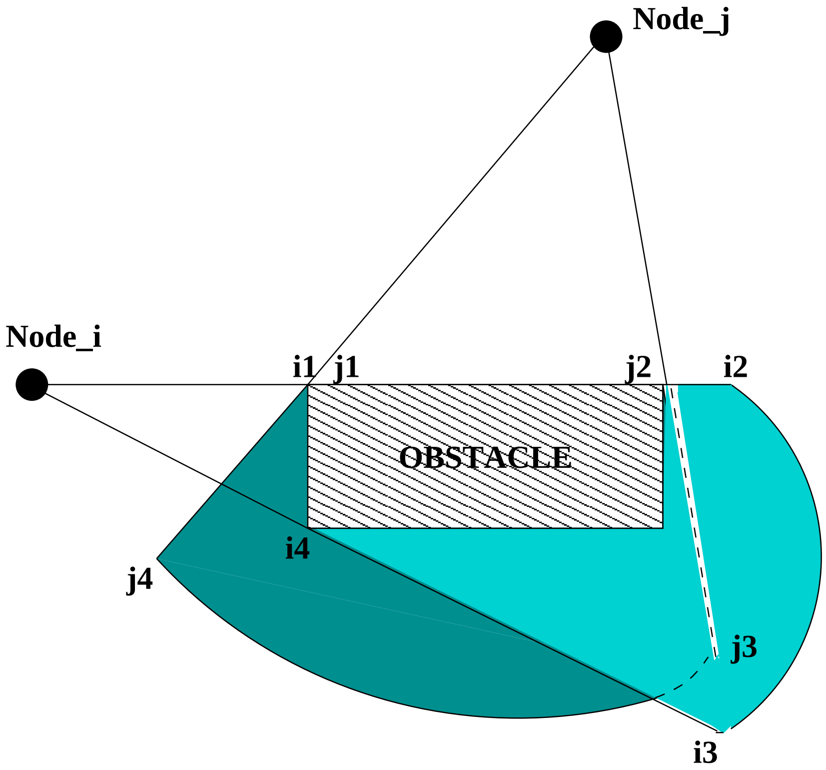

Figure 5.4: An example of two areas of dark.

In Figure 5.4 the case is represented. There are two potential transmitters $Node\_i$ and $Node\_j$ nearby to a rectangular obstacle. The figure shows that the area behind the rectangle is an area of dark where signals do not propagate at all. In particular, the dark areas for the two nodes are marked with different colors and delimited by four vertexes for each node. Obviously, these areas vary when mobile entities move, and they can be multiple for each node, whenever a node is nearby to more than one single block. Every MN r_i located in any of the areas of darkness of another MN s will not hear any radio signal sent from s.

The formula to calculate the signal strength in reception is reported in Equation 5.5. In particular, the equation is exactly the same of Two Ray Ground when no obstacles prevent the signals propagation, and it is zero otherwise. An obstacle *obs* is preventing a communication between a sender s and a receiver r, if the line joining s with r intersects the area of *obs* in at least one point. In this case we say that *obs obstructs s.*

$$P_{r-RPMO} = \begin{cases} 0 & \text{if } \exists \; obs \in O = \{obs_1, ..., obs_m\} \mid \text{obs obstructs s} \\ Pw_{r-TRG} & Else \end{cases} \tag{5.5}$$

An important observation to point out is that in my own radio propagation model, the distance d between two communicating nodes is computed in a slightly different way than in TRG. This is because I want to model an area that consists of the internal surface of a Torus. The network simulator, normally solely handles simulation terrains square-shaped or rectangular-shaped. The radio signals must be capable of propagating through the edges to obtain a torus. Since the receiving power is function of the distance, a modification to the algorithm that computes nodes distances is needed to implement signals propagation through the borders (see Equation 5.2).

In Figure 5.5 it is shown a possible travel patter for a mobile node randomly moving within a torus. What we see is how a MN can cross the borders without changing the direction of its movement (wrap around behavior). Furthermore, in the bottom right corner, it is shown the communication range for a node close to the edges when no obstacles are hindering the propagation. Note how the radio signals transmit through the borders.

5.3.4 A more Sophisticated RPM

NS2 provides a Radio propagation model which could be used for considering the presence of constraints to prevent total signals propagation in a simulation terrain [1].

To introduce random events, the *Shadowing Model* (SH) utilizes a random variable X. The shadowing model requires a reference distance d_0 to calculate the average received Free Space (FS) signal strength $Pw_{r-FS}(d_0)$. There is then a path loss exponent β which in Equation 5.6 depends on the simulated environment and is constant during the simulation. Its value depends on the environment and must be empirically determined. In [1] a few values between two (free space) and six (indoor, non line of sight) are suggested for certain frameworks. X is normally distributed with mean zero and standard deviation σ called shadow deviation. Formally:

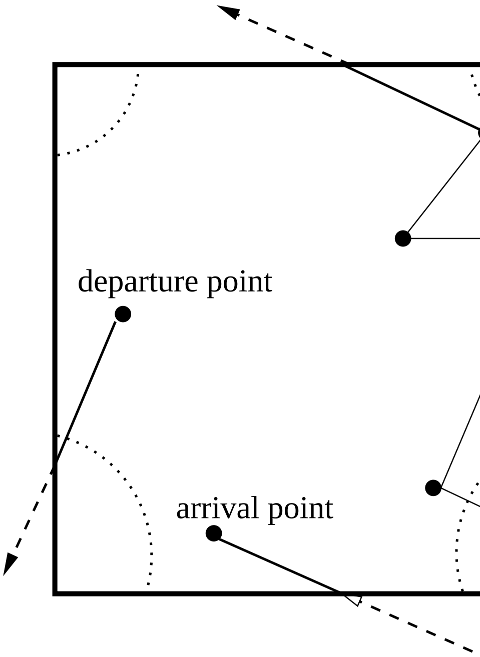

Figure 5.5: A random movement pattern for a MN internally moving in a torus.

$$Pw_{r-SH} = Pw_{r-FS}(d_0)\left(\frac{d}{d_0}\right)^{\beta} 10^{X} \tag{5.6}$$

- Where: $X(x) : \{x \in [-\infty, +\infty] | P(x) = N(0, \sigma^2)\}$.

Shortly, with this model correct receptions are guaranteed for close proximities, and impossible over long distances, whereas correct receptions are totally unpredictable for medium distances. The strength power varies significantly between consecutive transmissions, and even it differs for the reception of the same transmission at different receivers. In fact, every receiver will hear a certain power that is computed based on both the path loss exponent β, and the random variable X. Since neither of these two parameters is dependent on the receiving angle on the antenna, consecutive packets from a sender to the same receiver in a static scenario suffer from random loss packets.

This modeling fashion leads very close to real world measurements. In fact, typically the radio signal strength received does not only depend on the distance between sender and receiver. An additional very affecting factor is for instance the angle at which the signal arrives on the antenna. This means that two different receptions of the same transmitted signal may give different results even when the distance is equivalent. In Figure 5.6 it is displayed a possible real radiation pattern for an omnidirectional antenna [35]. The figure shows how the signal strength changes at different directions (angles).

The real model differs from the shadowing model (SH) formalized in Equation 5.6, in the fact that the radio signal strength does not vary in an unpredictable way, but rather it does precisely depending on the angle.

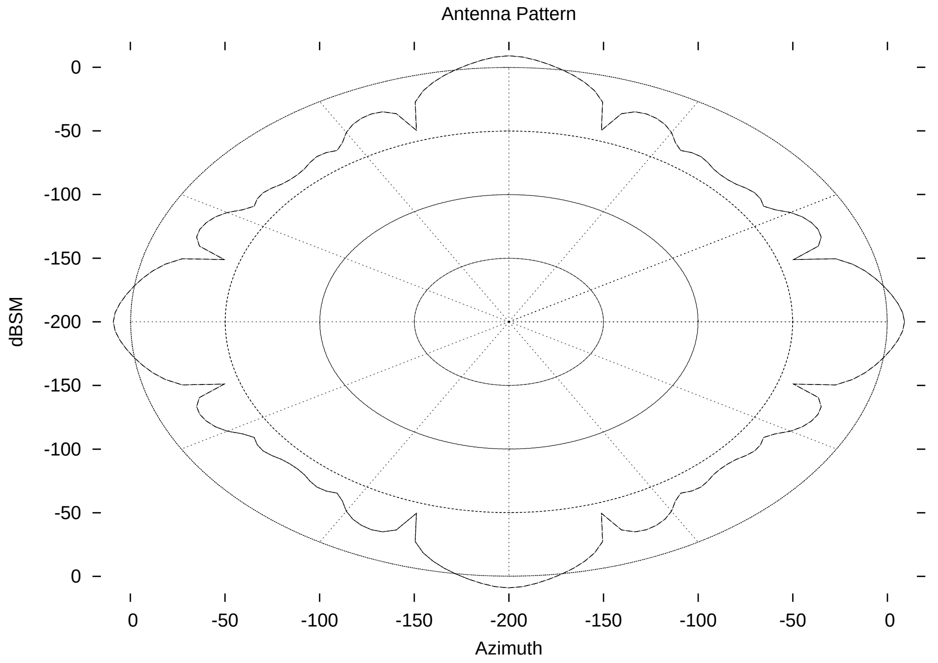

Figure 5.6: A sample plane radiation pattern for an omnidirectional antenna.

5.4 Hypothesis

The entity mobility model proposed should lead to observe that an Urban Environment significantly affects the protocol performance. In fact based on the writer's intuition, shadowing obstacles should decrease the performance.

Moreover, the particular and strict motion modeled might cause Mobile Nodes (MNs) to move in totally opposite directions probably introducing longer delays. On the other hand, there is a significant probability that two MNs will travel together for quite long time. If this occurs, protocol performance might increase by reducing the routing overhead needed for a successful communication. In a free mobility model, there are no guarantees that mobiles hearing each other will keep doing so also in the future. In fact, in most of the Statistical Patterns the nodes' direction vectors randomly differ of whatever value in $[0, \pi]$, either positively or negatively.

5.5 Implementation

The network simulator has been integrated with the presented Radio Propagation Model with Obstacles and the Torus extension.

Furthermore, a module to read in input the map of a city has also been developed. This additional module *MoveScen*, permits to read from a text file the physical description of the urban framework. The roads where nodes must move, and the crossing points have to be specified in the file. Once the city map has been correctly described, the module produces the set of movements needed to perform a simulation experiment as a *Scenario* file. The movements are generated with the fashion described in Section 5.1.

The set of obstacles must also be specified. In fact, thanks to an additional module implemented (*Obstacles*), the topological characteristics of a simulation terrain can easily be described directly in the TCL script. The obstacles can be solely specified to be rectangular, but many rectangles located close to each other (or even overlapping) form a generic shaped block.

The Enhancements of NS2 are publicly available as a package for torus and obstacle extension. The hope is that other networks researchers will find them worth to utilize.

Chapter 6

Simulations

This Chapter presents the simulation experiments that were done to test the previously proposed Urban Mobility Model (UMM).

Several scenarios were obtained by varying the input parameters among two mobility models (RWP, UMM), and two radio propagation patterns (TRG, RPMO). The possible combinations of pairs Mobility Model, Radio Propagation Model (MM,RPM), were tested by varying both the maximum speed of movement, and the size of the torus terrain. The particular routing protocol whose performance were measured is Dynamic Source Routing (DSR) [22, 23]; a commonly used reactive routing protocol.

The simulations were designed to comprehend the possible implications of the urban environment on the routing protocol performance. In particular, the interest was to observe how the placement of roads and the presence of buildings can affect the routing operations. Although, RWP shows unrealistic movement patterns in urban environment, and Two Ray Ground poorly models the signals propagation in the concerned framework, I still run simulations with RWP and TRG for comparison purpose with the other more realistic fashions.

6.1 The Experiments in Detail

Two set of experiments were run to show that the different pairs (MM, RPM) cause the routing protocol to perform differently. Three distinct pairs have been observed, and they are reported in Table 6.1. When using RWP mobility model the obstacle constraints were always off. In contrast, every time that UMM was employed, we evaluated two cases: first with the radio constraints i.e. obstacles *off*, and subsequently by setting them *on* and by using exactly the same movement directives.

Table 6.1: Different pairs (MM, RPM) that have been studied with experiments.

Pair referred to as:	*Mobility Model*	*Radio Prop. Model*
RWP	RWP	TRG
UMMoff	UMM	TRG
UMMon	UMM	RPMO

Thanks to the three pairs under study, I was able to investigate the impact of both the predefined movement pathways, and the inclusion of buildings. The aim was to show that a realistic situation prevents the routing protocol from performing at the top of its capabilities. This in order to gather enough confidence to claim that RWP and TRG do not accurately represent real life situations, and hence they should be used being aware of their limitations and inaccuracies. If verified, this claim should remain valid regardless the mobility conditions (speed of movement), and the size of the simulation surface.

Initially, a first set of runs were performed with both RWP and UMM by varying the maximum speed in $Vel = \{5, 10, 15, 20\}$ (m/s). In this manner, I studied how the different Mobility Patterns and radio propagation models affect the routing protocol performance in diversified mobility conditions.

Subsequently, a second slightly different set of experiments have been executed with both RWP and UMM by varying the size of the simulation area. The sizes under study were 800 m × 800 m, and 1200 m × 1200 m. In the final results there also appears the case of one kilometer square, which is the size used in the first set of simulations. These simulations were designed to evaluate whether different simulation terrains (in terms of size) lead the results to maintain the same tendency when the concentration of nodes $\frac{N}{Area}$ remains constant at $1/160m^2$.

In my experiments it was advisable to avoid evaluating results of a single simulation experiment that could have been characterized by peculiar happenings, not representative of the general situation. For this reason, I executed multiple simulations for each fixed set of input parameters. Precisely, 30 runs were executed with different random generator seeds. The results obtained were subsequently considered together and averaged. Doing in this manner, I ensured that the findings inclusive in this thesis are good representatives of each framework evaluated.

In each experiment, the simulation terrain was a "rolled" square to obtain a torus-shaped solid where MNs had a so called wrap around behavior.

Table 6.2: Summary of the simulation parameters.

Mob. Model			**Radio Constr.**		**Area Size (mt)**		**N**
	Speed Bounds			*Set of*	w	h	
Name	*Min*	*Max*	*State*	*Buildings*	*Width*	*Height*	
RWP	0	$\forall \nu_i \in Vel$[1]	off	$\emptyset$	1000	1000	40
UMM	0	$\forall \nu_i \in Vel$	off	$\emptyset$	1000	1000	40
	0	$\forall \nu_i \in Vel$	on	B[2]$\rightarrow \ \|B\| = 25$	1000	1000	40
RWP	0	20	off	$\emptyset$	800	800	26
	0	20	off	$\emptyset$	1200	1200	58
UMM	0	20	off	$\emptyset$	800	800	26
	0	20	on	$B \rightarrow \|B\| = 16$	800	800	26
	0	20	off	$\emptyset$	1200	1200	58
	0	20	on	$B \rightarrow \|B\| = 36$	1200	1200	58

In Table 6.2 the simulation parameters are summarized that were used for the experiments. The duration of the experiments, the features of the Mobile Devices, and the choices made for the communication pattern were common to all the experiments and they are stated in Table 6.3. In Section 6.1.2, a few additional parameters will be precisely described for the city map utilized, along with the mobility within it. Moreover, a more detailed description on how the author has chosen the most important input parameters will be provided in Section 8.2.

6.1.1 Simulation Time Phases

All the simulations lasted for a time t_{TOTAL}. This time can be seen as split up in three main phases shown in Figure 6.1: Initial, Central and Final.

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[1] This set is defined in Section 6.1.

[2] This set is defined in Equation 6.1.

Table 6.3: Simulations common parameters.

Simulation Intervals (sec)	
Parameter	*Value*
Initial transient time t_i	900
Simulation time t_s	900
dt	100
Total time t_{TOTAL}	1850
Mobile Device features	
MAC Link Layer Protocol	802.11 Wi-fi
IP Layer Protocol	IP-v4
Routing Protocol	DSR
Communication Range	250 m
Traffic Pattern	
Channel nominal bandwidth	2 Mbit/sec
Transport Layer traffic type	UDP
Application Layer traffic type	CBR
Sending frequency	1packet/sec
Packet size	8 byte
Communicating pairs	N/2

The *Initial* phase, $t \in [0, t_i)$, is a transient interval of time needed for having the MSs disposed in a manner which is representative of the mobility pattern being used [6]. Note that this is of particular importance when streets are being deemed, since the initial placement of the nodes is at the crossing points as described in section 5.1.1. The *Central* phase, $t \in [t_i, t_i + t_s)$, is the interval of time where the simulation truly takes part and produces the results. The *final* phase, $t \in [t_i + t_s, t_{TOTAL})$, is a very short instant of time needed to give a chance to the packets just sent or formerly queued, to be correctly delivered. This interval's wide has been established to be 50 *sec.* In fact, as noticed in a restricted set of runs done on purpose, never the queues in reception needed longer time to become empty. The communicating pairs began to transmit at $t = t_i - dt$ in order to have the routing tables already filled up when the real simulation begins.

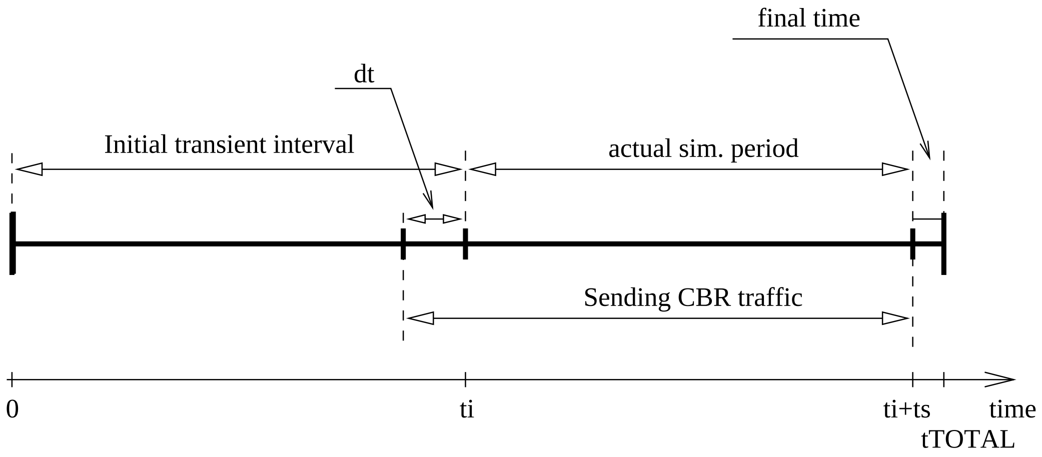


Figure 6.1: The time diagram of each simulation experiment.

6.1.2 UMM Input Parameters

In my implementation of UMM I have chosen as input parameters those reported in Table 6.4.

Table 6.4: Specified parameters for the City map.

Parameter	*Value*
Horizontal Step size H_s	200 m
Vertical Step size V_s	200 m
Probability of Pause P_p	0.1
Probability turning Left P_l	$(0.9 \cdot 0.2) = 0.18$
Probability turning Right P_r	$(0.9 \cdot 0.3) = 0.27$
Probability going Straight P_s	$(0.9 \cdot 0.5) = 0.45$
Time of departure	[0,30] sec.
Pause time	[0,30] sec.

When using the Urban Mobility Model (UMM) with the radio constraints activated, a set of shadowing buildings B had to be provided as an input parameter. In my model, the buildings in the city had square shapes, equal size ($100\ m \times 100\ m$), and neighboring buildings had the same distance from each other. These assumptions make the set of buildings B to be function of the map's parameters. Formally I define B as:

$$B = \left\{ b^{i,j} | (0 \leq i < N_v) \bigwedge (0 \leq j < N_h) \right\} \tag{6.1}$$

Where:

- The number of horizontal roads N_h, and Vertical roads N_v follow as specified in Section 5.1.1 i.e. respectively $N_h = h/V_s$ and $N_v = w/H_s$. Note that $|B| = N_h \cdot N_v$.
- A generic building $b^{i,j}$ is a building $b_{\overline{\nu}_1,\overline{\nu}_2}$ (see Section 5.1) with its left bottom vertex $\overline{\nu}_1 = (50 + i \cdot H_s, 50 + j \cdot V_s)$ and its right top vertex $\overline{\nu}_2 = (\overline{\nu}_{1x} + 100, \overline{\nu}_{1y} + 100)$. All the coordinates are expressed in meters.

6.2 Protocol Performance Measurement

As mentioned in Section 3.3, I had to choose the most suitable quantitative parameters to extract and analyze from the simulations' output. They must be good metrics to judge how the routing protocol (DSR) performed under the tested conditions.

In this section, I will shortly present all the quantitative parameters that I measured and analyzed for evaluating the protocol performance.

6.2.1 Packet Delivery Ratio

The *Packet delivery ratio* is the fraction between the number of data packets correctly received by all the receivers at their application layer, and the number of data packets originated by all the transmitters. This metric is very important since it describes the loss rate that will be seen by the transport protocol. In fact, the first aim that a routing protocol has to achieve, is being able to deliver correctly all the data packets. As intuitively the reader can comprehend, the higher the delivery fraction is, the better the protocol performance has been.

6.2.2 End to End Delay

The *End to end delay* is the time that the routing protocol takes to deliver a data packet from the transmitter's application layer, to the corresponding receiving one. This delay also includes possible time needed for either discovering an unknown route, or fetching it from the cache memory of the sending entity. The average delay is measured out of all the correctly received packets.

6.2.3 Path Length

The *Path Length* measures how many hops a packet needs to traverse before it actually reaches the desired opposite end point. Once again, the average is computed out of all the correctly received data packets. The concerned metric has been introduced to evaluate the protocol performance because the author believes this is a very important parameter to observe. Especially, when comparing the DSR's performance in a mobility pattern without any shadowing block vs. the same mobility model with radio signals propagation restrictions. It is certainly the average path length the metric whose value should drastically increase when it comes to add obstacles to the simulation map. Such an happening would reveal a protocol performance decrease.

6.2.4 Routing Overhead

The *Routing Overhead* is the total number of routing packets transmitted during the simulation. For packets sent over multiple hops, the packets count as one transmission per every hop traversed. This allows to keep in consideration the overall amount of control traffic generated by the protocol.

In the count of the routing packets are not inclusive neither the IEEE 802.11 MAC packets, nor the ARP packets. This is a rather natural choice due to the fact that a routing protocol could be run over a variety of possible medium access or address resolution protocols. Nevertheless, it is obvious that these protocols cause additional overhead messages to be introduced on the network. These packets are not related in anyhow with the network layer overhead messages. Wishing to evaluate the routing protocol performance itself requires to discard any type of additional overhead coming from other layers.

6.3 Network Topology

Different mobility fashions and diverse radio propagation models cause the network topology to vary depending on it. Hence, the network connectivity, and links stability are likely to differ depending upon the case. In order to achieve a better understanding of the results gathered from the simulations, the network connectivity should be investigated beforehand. Therefore, I analyzed the links duration distribution for each of the three situations studied. The following paragraph clears up the way I followed to compute the distribution concerned.

6.3.1 Links Duration Distribution

We say that there exist a link between two mobile devices (i, j), if their distance is smaller than the radio communication range R. Furthermore, when RPMO is being used, neither i must be in any of the areas of darkness of j nor j must be prevented to receive radio signals from i.

The *Links Duration* is a metric to describe how steady are the single links during the simulation. It is an index whose value should logically be strongly influenced by the mobility model being used. In particular, it should drastically decrease as shadowing blocks are placed in the simulation area.

In order to observe when a link breakage occurs, we need to fix a rather narrow time interval ω after which we will periodically look at the network topology. At every instant of time $t_k = k\omega$ we will be then able to know whether or not any link breakage occurred, based on the topology previously recorded at t_{k-1}. After that the simulation time T runs out, we will exactly know how many links breakages there have been.

- Let $X_{i,j}(t)$ be an indicator random variable with value 1 iff at the instant t there is a link connecting the nodes i and j.
- Let $B_{i,j}(t_k)$ be an indicator random variable such that $B_{i,j}(t_k) = 1$ iff $X_{i,j}(t_{k-1}) = 1$ AND $X_{i,j}(t_k) = 0$ i.e. iff there has been a transition from up to down (a breakage) for the link between the mobiles i and j.
- The number of times a link connecting i, j broke throughout the whole simulation period is given by the following:

$$LB_{i,j} = \sum_{k=1}^{\frac{T}{w}} B_{i,j}(t_k) \tag{6.2}$$

At this point it is trivial to introduce a probability distribution for the links duration. We consider only the pairs of nodes that have been connected for some period before breaking. The reason not to consider links that have lived but never died, is reasonable to avoid under determining the links duration values.

- Let $P(A \leq l < B)$ denote the probability that a randomly chosen link, among those considered, lasts for a time $t \in [A, B)$.
- Let $l_{i,j}^{Q}$ denote the number of times the link between i and j has been observed up for exactly Q instants in a row before going down. Observe that in such a case the real duration d is given by $d \in [(Q-1)\omega, Q\omega)$.
- Let N denote the number of nodes that compound the mobile network. We assume that these mobile terminals are named with an integer index $h \in \{0, 1, ..., N-1\}$.
- The desired probability distribution is given by the following:

$$P(t_{k-1} \leq l < t_k) = \frac{1}{\sum_{i=0}^{N-2} \sum_{j=i+1}^{N-1} LB_{i,j}} \sum_{i=0}^{N-2} \sum_{j=i+1}^{N-1} l_{i,j}^{k} \qquad (6.3)$$

In order to gather complete data it is necessary to vary $k \in \left\{1, 2, ..., \frac{T}{w}\right\}$. From the distribution computed with the Equation 6.3, we can infer the probability that a single link lasted for a generic period of time. The above equation has been used in my experiments with ω as small as 5 *sec* during the actual simulations.

Chapter 7

Results

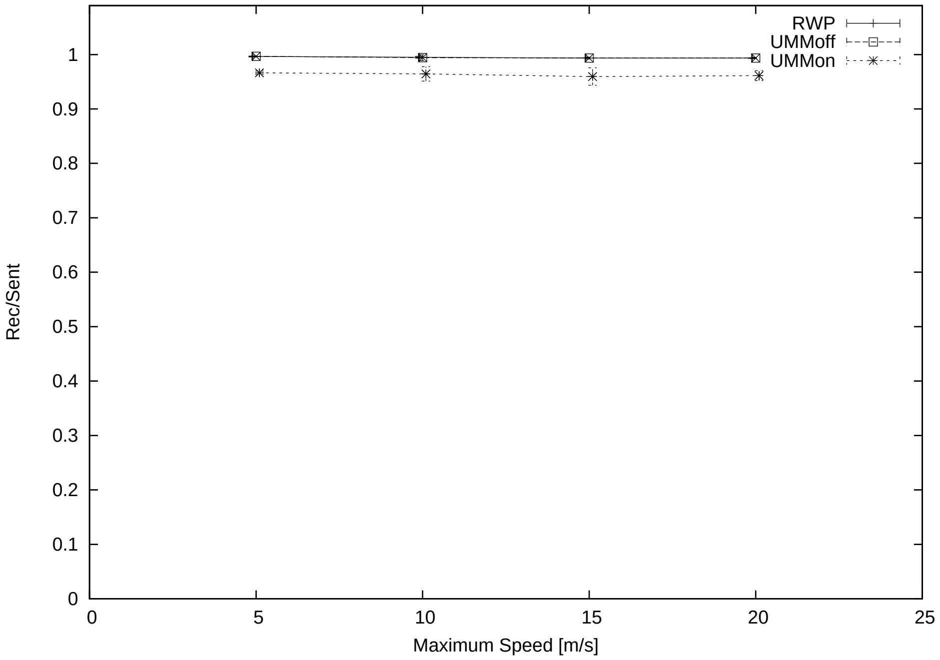
This chapter presents the final simulation findings gathered from the experiments. The performance evaluation will be made in respect with those metrics introduced in Section 6.2.

The results show the overall routing protocol behavior seen in multiple experiments; i.e. each of the points drawn is the average of thirty different experimentations. Additionally, in order to provide the reader with an idea of the data variability within the thirty runs represented by each point, upper and lower estimates that represent 95% confidence interval are shown.

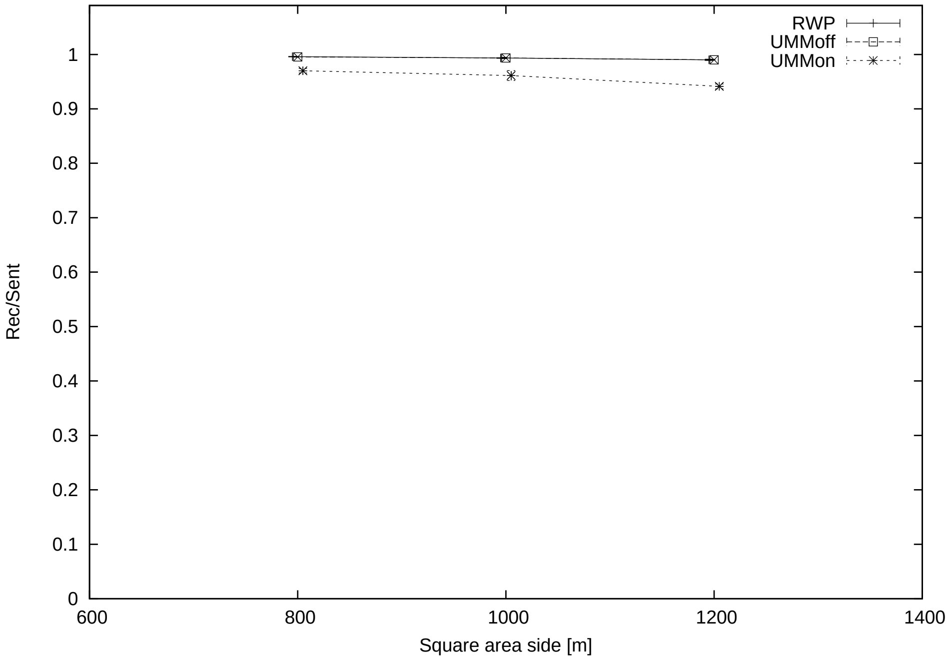
All the diagrams here inclusive depict three different curves: one for each of the studied pairs (MM,RPM). Moreover, depending upon the particular set of simulation being referred, you will see appearing on the abscissas either the maximum speed of movement, or the size of the simulation terrain.

Specifically, Figure 7.1 depicts the network throughput in terms of delivery ratio. Subsequently, Figures 7.2, and 7.3 respectively portray the average end to end delay and the average numbers of hops. Concluding, the network overhead in terms of signaling messages is displayed in Figure 7.4. Each figure is compound of two parts (a,b) to differentiate the results obtained from the simulation Set 1 and Set 2.

All the findings here enclosed, will be further analyzed through Chapter 8.

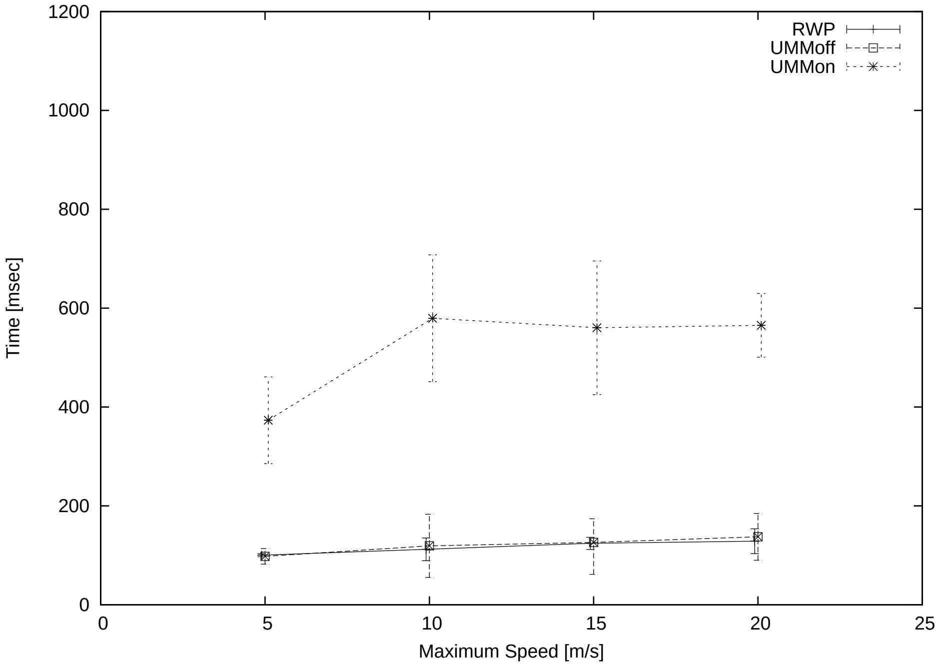


(a) Set 1, variation of the speed.

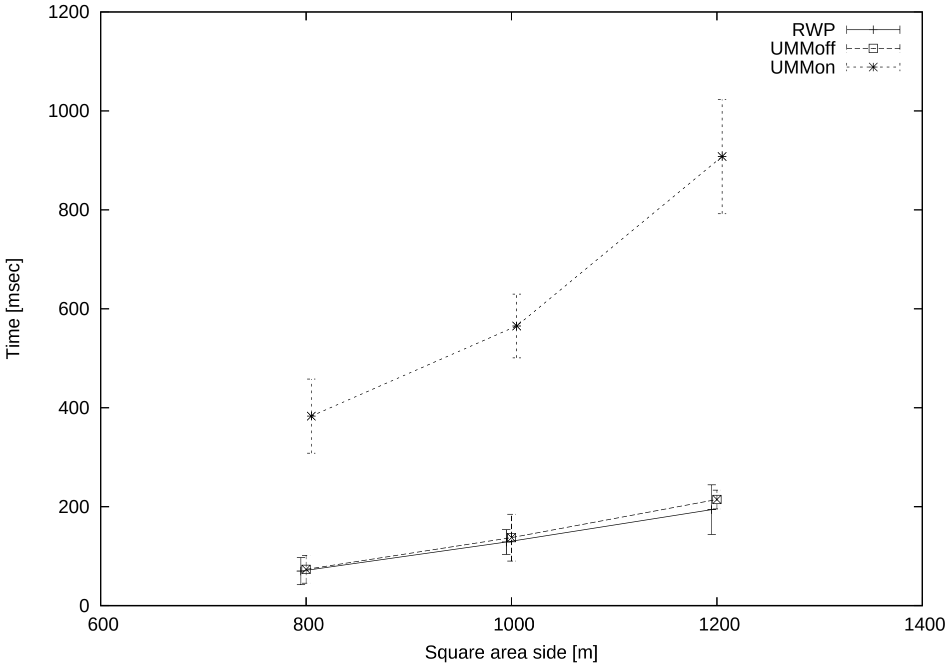


(b) Set 2, variation of the surface size.

Figure 7.1: The delivery ratio.

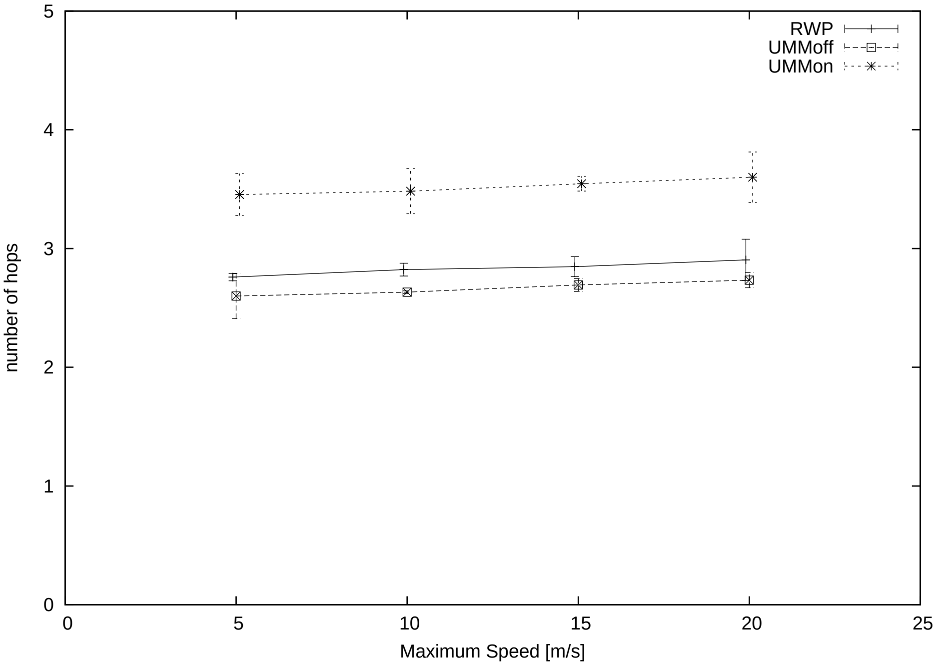


(a) Set 1, variation of the speed.

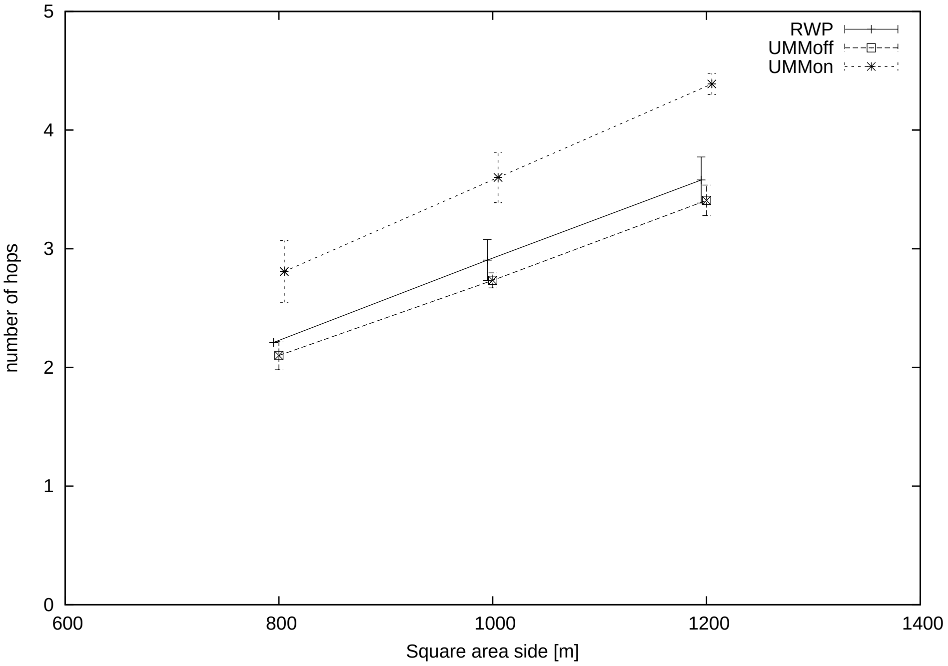


(b) Set 2, variation of the surface size.

Figure 7.2: The end to end delay.

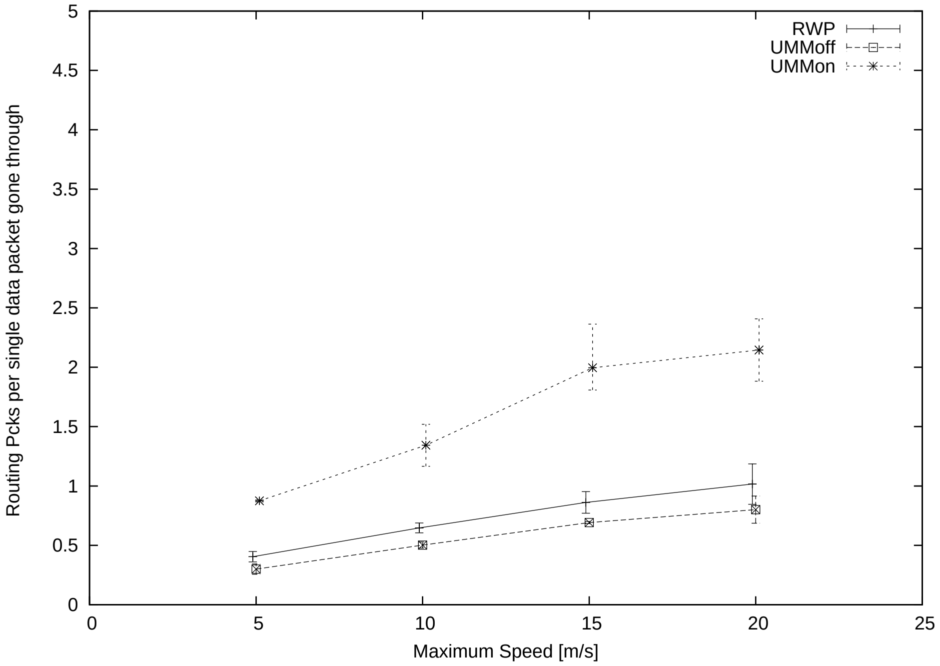


(a) Set 1, variation of the speed.

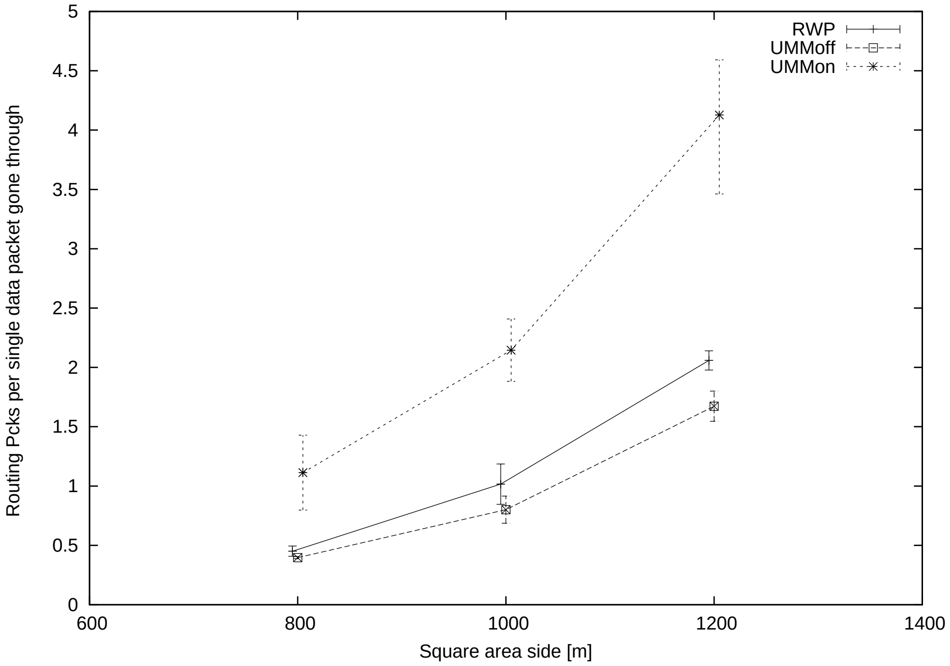


(b) Set 2, variation of the surface size.

Figure 7.3: The average path length.



(a) Set 1, variation of the speed.



(b) Set 2, variation of the surface size.

Figure 7.4: The average number of routing packets per single data packet gone through.

Chapter 8

Analysis

This chapter presents the analysis of the results obtained from the simulation experiments. Particularly, it will clarify the reasons that lead the proposed Urban Mobility Model to cause the routing protocol to perform as shown earlier. This in comparison with the more commonly used fashion provided by RWP.

From now on the analysis will comment the results by referring the experiments to as *Set 1* and *Set 2*. Respectively indicating those simulations where the speed of movement varied first and the size of the simulation area varied then.

Before going through the analysis, it is shortly recalled the basic principle of functioning of the routing protocol DSR already introduced in Section 2.3.

8.1 Understanding the results: DSR's functioning principle

As already mentioned, DSR is a reactive routing protocol that allows nodes to dynamically discover a route across multiple network hops to any destination. DSR uses no periodic routing messages (e.g no periodic advertisements), thereby reducing network bandwidth overhead compared with all those protocols which are proactive. In particular, such a protocol guarantees an overhead close to zero in stationary conditions of the network.

The manner how DSR finds and keeps consistent the routes consists of two phases; respectively, they are referred to as *route discovery* and *route maintenance.*

Route Discovery

Route Discovery is the mechanism by which a node S wishing to send a packet to a destination node D obtains a source route to D. Route discovery is used only whenever the sender is in need of the route just before performing a transmission. Hence, it is invoked solely when the transmitter does not have in its cache a route previously learned.

A route discovery operation consists of broadcasting a Routing Request (RR) to all the neighbors that will propagate the request further in the network. As soon as the request reaches a mobile that knows a route to the destination, a Route Reply containing the route is sent back to the originator node.

Several mechanisms, to reduce the traffic originated by the broadcast operations, are adopted. Likewise, mechanisms to permit nodes to learn and cache new routes from others' packets overhead do exist.

Route Maintenance

Route Maintenance is the mechanism used by DSR to detect a previously established route to a destination that is no longer available. This happens whenever a single link breakage occurs along a path due to nodes movement.

Possible breakages are brought to the attention of the sender thanks to a Route Error (RE) message that is sent back to it from intermediate nodes. These intermediate nodes can treat a link as currently "out of order" whenever they do not receive an acknowledgment of the message put into it. This mechanism relies on MAC capabilities of positive acknowledgment.

8.2 Consistency of the Experiments

Among the numerous input parameters chosen for the simulation experiments, some came from a restricted set of simulations performed beforehand on purpose. These parameters were those that intuitively were deemed to be the most important that may have an impact on the results. Others, intuitively less critical, have been established according to similar previous work instead. Taking advantage of earlier researches makes the results comparable and it guarantees that the values actually chosen are reasonable to be used.

The choice of running a few simulations beforehand, ensures that the final results are consistent. In fact, it is highly undesirable to run experiments that lead to draw misleading conclusions owing to an erroneous choice of the input parameters.

Concentration of Nodes

The *Concentration of nodes* per unit of area is a basic parameter whose value must be properly chosen. In fact, a too small value may lead to have an insufficient coverage of the entire terrain. The side effect in such a situation is that the routing protocol would be prevented from successfully achieve its objective. For instance, the data delivery ratio could assume unacceptable values caused by a too sparse network that splits in several partitions.

Likewise, introducing an excessive amount of MNs could also lead to undesired side effects. In fact, not solely the network would result to be overloaded beyond the available bandwidth, but also a considerable additional computational complexity and simulation time would be introduced with no reasons. The computational complexity is a limiting factor when simulating networks with NS2. In fact, its algorithms' complexity is quadratic in the number of nodes.

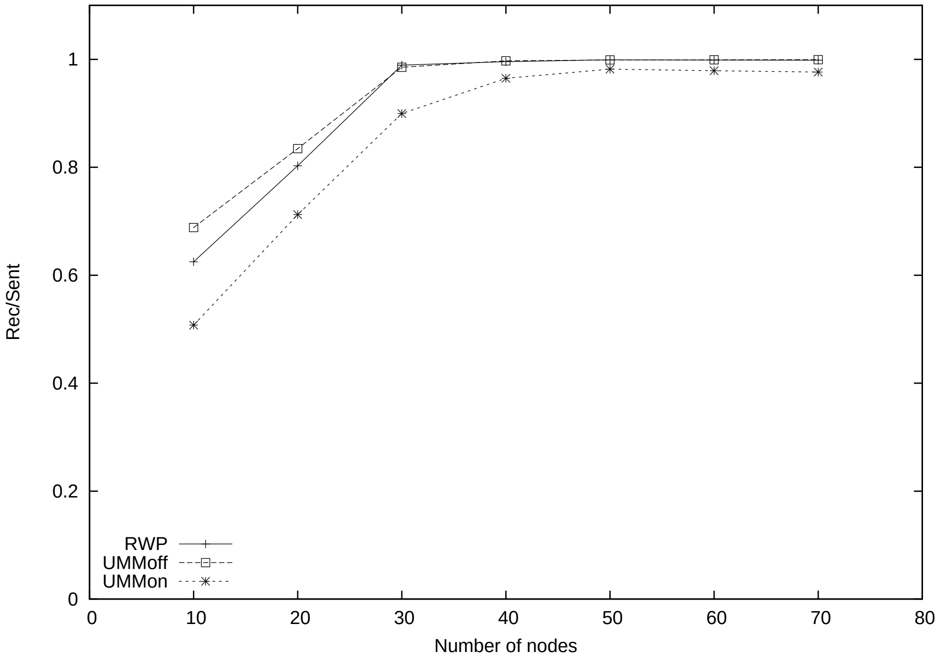


Figure 8.1: The data delivery fraction vs. the number of nodes in a simulation terrain of 1000 m^2.

In Figure 8.1 it is depicted the situation observed by averaging two experiments for each value of the abscissas. The simulations were run in a terrain of one kilometer square of area, using an initial transient of time of 1000 sec, having $N/2$ pairs of nodes communicating, and with a max speed of $20m/s$. The motivation to select a high speed comes from the fact that faster MSs should make the protocol's duty harder. Hence, the the right concentration of nodes observed with high mobility, is expected to be suitable for any smaller speed as well.

As clearly shown, any amount of nodes over 40 puts the routing protocol in condition of fully operate. The figure does not show the maximum limit of nodes after which the network becomes overloaded. This data was not fundamental for establishing the right concentration of nodes to be used in the very simulations. Hence, I did not go any further because the computation complexity of the simulations was leading to exceed any reasonable running time.

In my simulations, the mobile terminals were always exchanging a relatively small amount of data (short data packets). This clarifies the reason why the network does not easily become congested.

Initial Transient Interval

The *Initial transient interval* of time needed to have the nodes disposed in a manner that is representative of the mobility model under study is another fundamental and important parameter. Particularly, as underlined in Section 4.3.1, the mobiles need a certain time to get the network in a steady state. Typically, it is insufficient to initialize the system by locating the nodes randomly in the simulation area.

The undesired side effect that occurs is that there are some initial fluctuations in the average number of neighbors over time. This is because of an initial uneven coverage of the terrain by the nodes. They need to be shuffled further in order to have a significant disposition.

My interest is to make sure that the actual simulation begins only after that the initial fluctuations have minimized. Moreover, I also want to be certain that the fluctuations have just stabilized to be able to minimize the total simulation time, as well as the computational resources needed.

In Figure 8.2 it is shown the diagram obtained by averaging the number of neighbors in two different very long experiments. The speed chosen for these tests was as small as $5m/s$; it is hence ensured that the initial transient

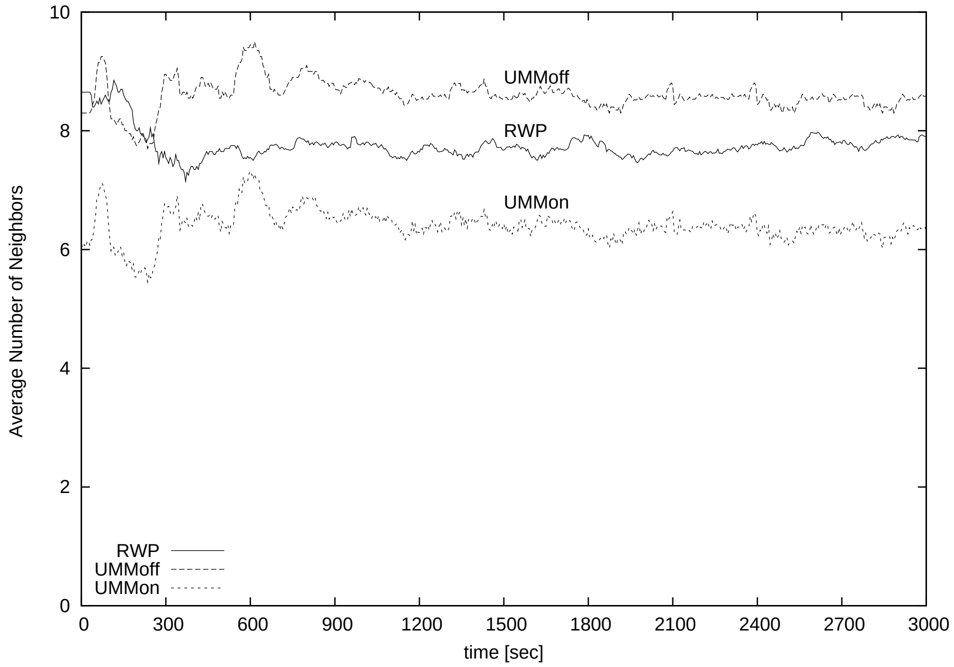


Figure 8.2: The average number of neighbors observed over time when the max speed was set to be 5m/s.

of time inferred is suitable for each other simulation as well. In fact, it is expected that when the velocity of movement is higher, the network becomes stable earlier.

From the diagram we see the initial fluctuations to be lasting for less than 1000 sec in all the mobility fashions. As the reader might observe the curves of *UMMoff* and *UMMon* have a certain similarity. This is because the MNs moved according to the same directives.

Other Input Parameters

Parameters that were not deemed to be critical were all those belonging to the traffic pattern such as packet size, sending frequency and number of flows. The type of the communicating flows was *Constant Bit Rate*. CBR gives the best estimate of how the network can deliver data without the fuzziness of upper layers that may utilize some own mechanisms e.g. TCP.

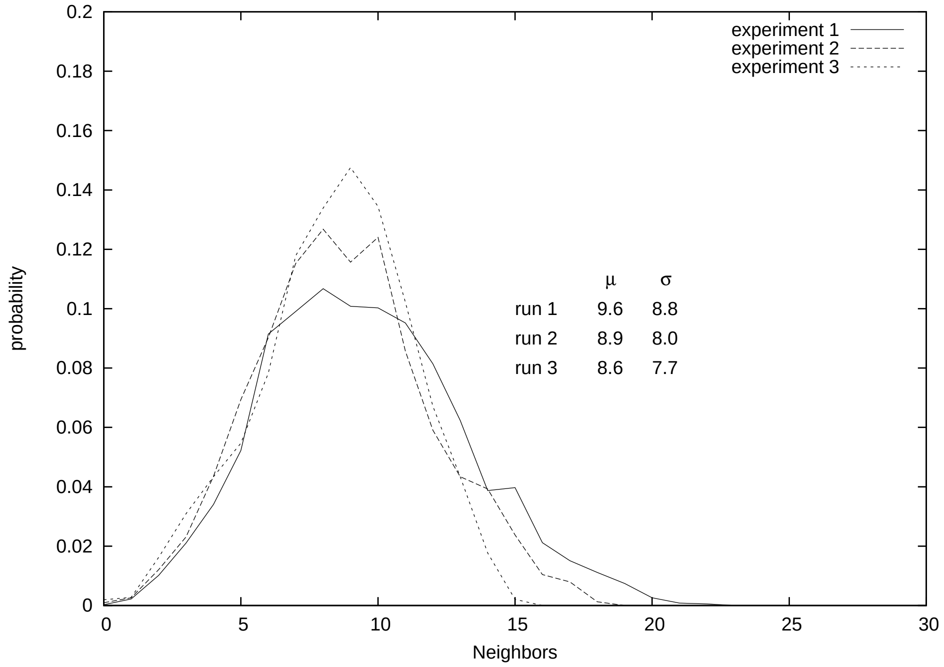
The traffic pattern is certainly an important aspect of the simulation, but it is not this thesis' aim to investigate it in detail.

8.2.1 Repeatability

A second aspect, that contributes to achieve consistent results is related with the *repeatability* of the simulation experiments. Once we have established all the input parameters for the simulations, we still are not certain that diverse experiments have a low variability between each other.

Since all the mobility directives are randomly established for every single experiment, it is important to compare a restricted set of multiple runs to check out their similarity. Once again, the properties that I checked are related with the disposition of the MNs within the area. Therefore, the metrics being observed are the distribution of the number of neighbors, as well as the links duration distribution.

It is expected that different runs with similar number of neighbors, and links duration distributions lead DSR to perform similarly ensuring a low variability in its performance.



	μ	σ
run 1	9.6	8.8
run 2	8.9	8.0
run 3	8.6	7.7

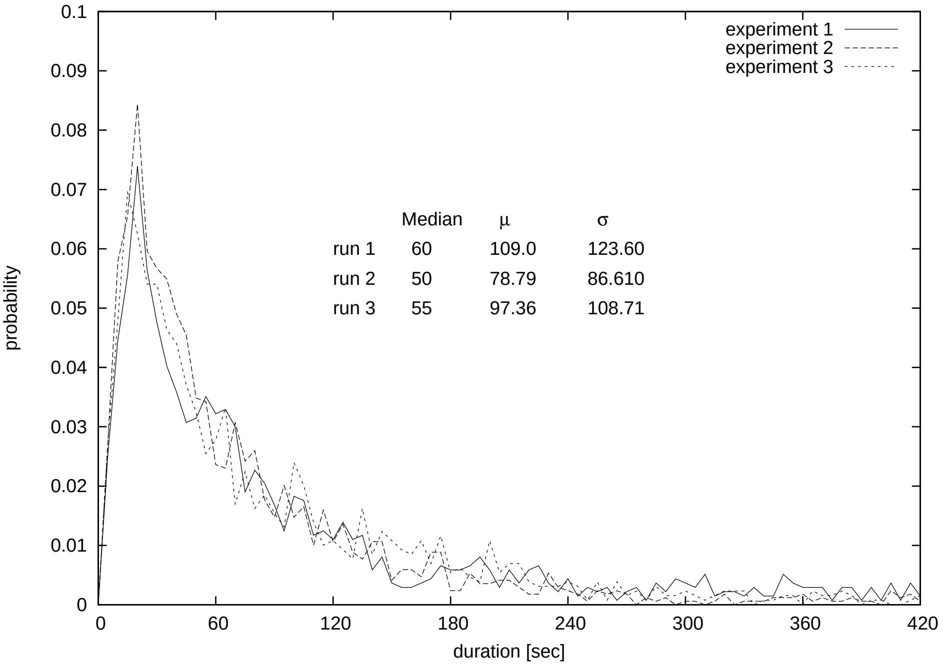
Figure 8.3: The neighbors distribution observed in three different single runs.

The Figures 8.3, and 8.4 portray the similarities observed in three single runs. According to the consistency tests, the initial transient of time and the concentrations of nodes were fixed to be respectively $900sec$ and $1/160m^2$.

The speed of movement was set to be $20m/s$, and the mobility pattern being observed was *UMMoff*.

In both figures we see that the curves have a similar tendency regardless the single run. As shown there are slight variations underlined by the mean, standard deviation and Median values reported. They are reasonable to be expected because of the randomness involved generating the motion directives. It is hence ensured that multiple runs are fairly repeatable.

As the neighbor distributions are roughly normally distributed, the mean is a significant statistic to compare. In contrast, since the link duration has a distribution that is highly skewed, the median provides a more informative measure. In fact, it is less sensitive to extreme scores than the mean.



	Median	μ	σ
run 1	60	109.0	123.60
run 2	50	78.79	86.610
run 3	55	97.36	108.71

Figure 8.4: The links duration distribution observed in three different simulation runs.

8.3 Mobility Patterns' Comparison

This section will analyze the very results shown in Chapter 7. The analysis will focus on pointing out the probable reasons that lead DSR to perform as actually observed for each of the three different pairs (MM,RPM).

Links Duration Distribution

In Table 8.1 is reported the *links duration distribution* seen analyzing the simulation Set 1 for the case in which the speed was $20m/s$. Each row in the table, shows the percentage of links that lasted for a certain period of time within an interval. Moreover, the most three right columns contain the cumulative percentages referring Short, Medium and Long lasting links.

Table 8.1: The average links duration distribution in case of speed 20 m/s.

		Detailed			**Cumulative**		
		RWP	*UMM*		*RWP*	*UMM*	
duration	$A \leq ld < B$		*off*	*on*		*off*	*on*
Short	$0 \leq \text{ld} < 20$	11.00	15.12	32.47	46.19	53.42	66.18
	$20 \leq \text{ld} < 40$	17.59	23.27	20.54			
	$40 \leq \text{ld} < 60$	17.60	15.03	13.17			
Medium	$60 \leq \text{ld} < 120$	33.87	24.94	19.62	52.74	44.66	32.68
	$120 \leq \text{ld} < 180$	11.02	10.26	7.25			
	$180 \leq \text{ld} < 240$	4.21	4.90	3.10			
	$240 \leq \text{ld} < 300$	2.02	2.29	1.40			
	$300 \leq \text{ld} < 360$	1.00	1.37	0.82			
	$360 \leq \text{ld} < 420$	0.62	0.90	0.49			
Long	$420 \leq \text{ld} < 480$	0.38	0.6	0.39	1.07	1.92	1.14
	$480 \leq \text{ld} < 540$	0.25	0.40	0.29			
	$540 \leq \text{ld} < 600$	0.18	0.30	0.19			
	$600 \leq \text{ld} < 660$	0.11	0.27	0.11			
	$660 \leq \text{ld} < 720$	0.06	0.13	0.06			
	$720 \leq \text{ld} < 780$	0.05	0.12	0.06			
	$780 \leq \text{ld} < 840$	0.03	0.05	0.03			
	$840 \leq \text{ld} < 900$	0.01	0.05	0.01			

From the table we learn that:

- In all the patterns, there are many links that lasted for a very short period of time. The ranking is *UMMon*, *UMMoff*, *RWP*.
- Medium duration links are also very numerous but not as much. In this case the ranking is *RWP*, *UMMoff*, *UMMon*.
- Long lasting links are very small in percentage in all the cases. The ranking is *UMMoff*, *UMMon*, *RWP*.

As shown in the Table above, over fifty percent of the links in *UMM* only last for less than one minute. There are two key factors that lead the proposed model to have these dominant probabilities. Specifically, the Realistic Motion and the Strict Signal Propagation.

The presence of pathways contributes to make the probability of having short lasting links rather high for both *UMMoff* and *UMMon*. In fact, when two neighbors travel along the same street with anti-parallel directions, they are certainly subject to remain in each other's transmission range for only a short period of time. The described situation may occur in the *RWP* fashion as well, however since there are no roads it does more rarely.

Likewise, the presence of buildings counts as factor that additionally raises the amount of links breakages. As an example, think of two mobiles moving with perpendicular directions that become neighbors when approaching a crossing point. In this situation their wireless connection cannot last long; in fact, the two mobiles are entering each other's area of darkness. Thus, their traveling pattern will cause a link breakage as soon as their distance will start growing. Additional and repetitive wireless breakages also occur when two terminals move on parallel directions along two adjacent streets.

Concerning the long lasting links, they are obviously very small in percentage. The fact that the speed of movement being considered is rather high, contributes to keep these percentages very small. In both the fashions with streets the long lasting links outnumber those of the *RWP* case. The explanation for it comes from the particular values chosen as probabilities of turning in UMM. In fact, as they are stated in table 6.4, turning right is more probable than left. The effect of this is that a group motion is favored. Hence, in this circumstances the links are subject to remain stable for longer time.

I enclosed only the table considering the speed being 20m/s. Though, the tendency observed remains similar regardless the particular velocity.

Delivery Ratio

In Figure 7.1 it is portrayed how the routing protocol was able to deliver the data packets depending on the chosen maximum speed (a), and depending upon the simulation terrain's size (b). The delivery fraction can be thought of as a measure to judge the throughput of the network.

What we see is a quasi-optimal performance for both the *UMMoff* and *RWP* conditions. In contrast, when it comes to regard obstacle constraints in the city framework *UMMon*, the packet loss increases drastically to make the data delivery ratio going down of roughly five percent. This peculiarity is reasonable to be expected since the mobiles are more likely to suddenly disappear behind some building block. Such a situation leads the mobile entities to lose the ability to communicate with other nodes that were neighbors when blocks were considered to be transparent to the radio signals in the *UMMoff* conditions. In other words, existing links in *UMMon* may remain stable for a relatively shorter duration. This leads more packets to be dropped due to link breakages, resulting in a lower overall throughput.

Surprisingly, it was observed that no evident difference exists between a Random Way Point pattern of movement and a model where movements are constrained by a set of pathways. This regarding the concerned metric and regardless the speed of movement and the size of the area. The current result says that the protocol fully operates with success, regardless the particular mobility pattern employed. Though, a further analysis looking at other metrics, will subsequently explain how DSR achieves even results for these two fashions. The routing overhead required for achieving equivalent results is likely to be different.

End to End Delay

In Figure 7.2 it is depicted the data packet average latency observed during the two simulation set.

In figure part (a) the average end to end delay shows a very slight growth proportional to the increase of the maximum speed of movement. Nodes that move faster lead the network connectivity graph to change sensibly over time. Hence, link breakages invalidate the routes that need to be discovered more often. The cost is obviously an increase in the average delivering time. In fact, data packets must remain in the transmitter's outgoing queue for longer time, while a new route to their destination is being discovered. Part (b) displays how a wider simulation surface also introduces additional delays. They are originated by the need to follow routes that become longer proportionally with the size of the area (see Figure 7.3(b)). In fact, when the radio communication range remains constant and the simulation area grows in size, the average distance that separates two end points increases. Thus, even the entities move within a torus solid, wider simulation surfaces require the usage of more relays to cover the distance between a transmitter and the respective receiver.

In either the parts of the figure (a),(b), RWP and UMM with no barriers to obstruct the radio waves, have both roughly the same curve. Unlike, looking at the *UMMon* curve, it results evident the immense additional latency introduced by the presence of buildings. This additional delay comes from three factors: longer routes, longer route discovering time and a larger amount of Route Requests (RRs) to be performed.

The author believes the first contributes in a very small amount. In fact, from figure 7.3 we see that the average routes length difference between *UMMon* and *UMMoff* is roughly one hop that might cost up to only 40-50 msec. From a further analysis to the experiments Set 1, it has been noticed that a more significant delay is caused by the time required to find the route for an outgoing packet that yet does not have one. In fact, the analysis revealed the time needed to be about six times bigger in *UMMon* in comparison with *UMMoff*. Furthermore, it has been observed that in the *UMMon* fashion, the route discoveries that are needed outnumber those of the model solely having streets.

Since in both the cases the amount of data flows and the sending rate were common, we can infer that the routes are subject to last for a shorter period of time. Therefore, more RRs are needed to be sent out by the transmitters. To strengthen my justifications, I enclose in Table 8.2 the average values observed for the route discovering times and the number of Route Requests needed. The data are presented depending on the velocity of the MNs when the simulation terrain was a square of side $1000m$. The table reports percentages for each model in comparison with the *UMMon* case that has shown the worst performance.

Table 8.2: Relative amount of route discoveries in different mobility models compared with *UMMon* case.

Max Speed	**Time to find a route**			**Number of RRs**		
	UMMon	*RWP*	*UMMoff*	*UMMon*	*RWP*	*UMMoff*
5	100%	26%	14%	100%	35%	24%
10	100%	26%	20%	100%	39%	29%
15	100%	26%	16%	100%	39%	31%
20	100%	23%	16%	100%	43%	33%

Hence, the overall effect that introduces the immense delay in case of *UMMon* is originated by routes that are found at high cost and that need to be set up again after being utilized for only few deliveries. In contrast, in both *RWP* and *UMMoff*, not only the routes are discovered at low cost, but also they last longer which is a double advantage.

To confirm this final observation, Table 8.3 shows the average number of data packets that were sent along the same route before that a breakage occurred.

Table 8.3: Average number of data packets sent out by the transmitters along a common stable route.

Max Speed	**Data Packets sent**		
	UMMon	*RWP*	*UMMoff*
5	24.91	49.42	68.69
10	16.15	28.82	39.08
15	11.32	20.90	26.25
20	10.15	17.56	22.64

Path Length

In Figure 7.3 it is displayed the average number of hops traversed by those data packets that have eventually gone through.

Figure 7.3(a) suggests that the average routes length does not change, or it does slightly depending upon the maximum speed of movement. This result makes sense since, from the consistency tests previously performed, we ensured that the mobiles get in a representative and steady state of their disposition after the ignored, initial transient. The nodes density remains the same over the simulation time. Therefore, different speeds do not contribute in anyhow to change the mobiles spatial distribution. Thus, regardless the particular speed of movement, the average number of neighbors per MN remains roughly constant, and the routes used are compound by the same amount of links. Unlike, in Figure 7.3(b) it is displayed a linear increase of the routes length depending on the size of the simulation terrain. The finding was reasonable to be expected because wider simulation surfaces increase the probability, in order for two communicating entities, to be separated by a longer distance. Obviously, a wider distance between two end points can only be covered by relying on more relays.

Other interesting finding which comes out from the concerned diagrams (a), and (b) is that when nodes move along the city streets *UMMoff*, the data packets are delivered through shorter paths compared with both *UMMon*, and even *RWP* pattern.

It is easy and intuitive to explain why the presence of buildings *UMMon* lengthens the routes compared with the same scenario without them *UMMoff*. In fact, when a node wants to communicate with a peer which is hidden behind a block, it needs to utilize one or more relays in order to be able to establish a data flow with its target node. What the graph suggests is that when obstacles obstruct the transmissions, one additional relay on average is required compared with the case of having transparent buildings.

The author believes that this increase is certainly dependent on the radio communication range of the entities, but also is subject to be dependent on the size of the obstacles. In fact, as soon as we will have bigger blocks, two nodes at opposite sides will need to rely on more repeaters in order to allow the radio signals to surround the blocks.

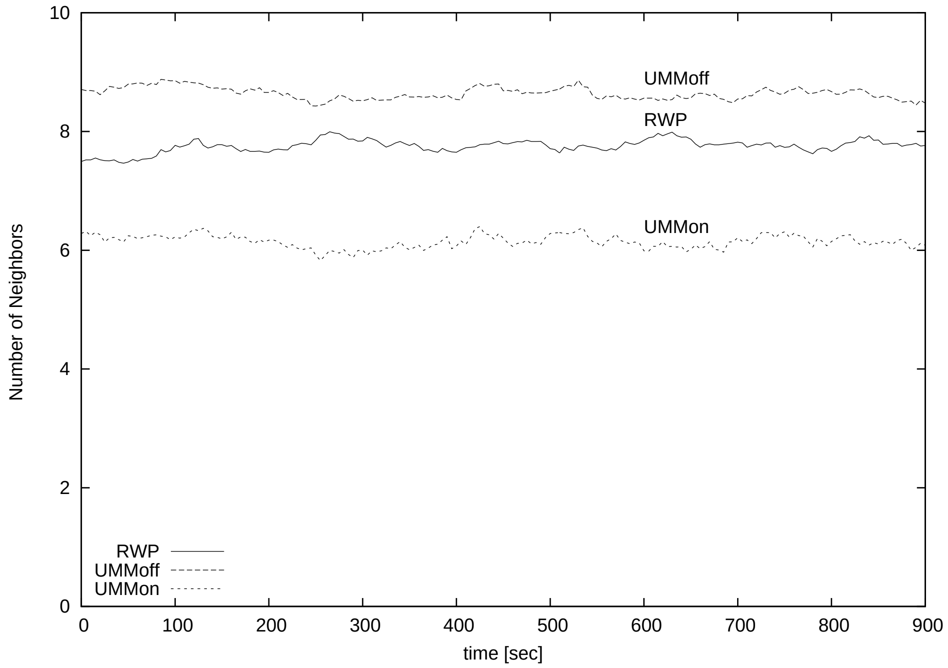


Figure 8.5: The average number of neighbors over time when the speed is 20 m/s.

More tricky it is to explain why *UMMoff* showed shorter routes in comparison with *RWP*. Even though, in either of the cases there is a 360 degrees omnidirectional transmission range, *UMMoff* has constantly a higher density of neighbors over time. The situation is depicted in Figure 8.5. Having a higher density of neighbors increases the probability, in order for a sender, to have its receiver closer in terms of number of hops.

The reason, why on average the neighbors in *UMMoff* outnumber those of *RWP*, follows from the fact that the roads prevent MNs from being located somewhere else than on the streets themselves. Since the nodes can only traverse the predefined pathways, the area of the simulation terrain that can be occupied by a mobile is reduced. Thus, a higher clustering is implied and a bigger amount of neighbors is constantly observed. Obviously, in the fashion with shadowing buildings the fact of not having a 360 degrees omni-directional transmission range limits the average number of neighbors of *UMMon*.

Routing Overhead

In Figure 7.4 it is displayed the average amount of control traffic required to correctly deliver a single data packet.

We observe from Figure 7.4(a) that different mobility conditions, in terms of speed of movement, affect the amount of control traffic to be introduced into the network. The reason is that the routes are liable to have longer durations when the velocity is smaller. Hence, as we increase the speed at which the entities roam in the terrain, the routing protocol must cope with more frequent Route Requests. Each of these messages originates further control traffic to be propagated through the network. Such a behavior is typical of reactive routing protocols which experience harder life as the mobility degree increases. From Figure 7.4(b) the evident result is that the routing traffic needed to correctly deliver a data packet drastically grows with the size of the terrain. The explanation is directly related with the average number of hops that separates two end points. In fact, as mentioned in Section 6.2.4, I am counting all the needed control packets transmitted over each single link. Longer routes cause a more massive flooding of whatever routing message. Therefore, increasing the simulation area in size, by preserving a constant concentration of nodes, leads the routing protocol to put more effort to successfully deliver each data packet.

Focusing on a comparison between the three distinct pairs (MM,RPM) we see a similar situation seen for the metric *Path Length*. The city environment without shadowing blocks *UMMoff*, is the easier scenario to be handled by the routing protocol. In contrast, the city framework with buildings *UMMon* requires a significant additional effort in terms of control traffic to be put into the network.

The increase in number of control packets that we see in the case of *UMMon* is certainly due to a shorter links life time. Therefore, the routing protocol is forced to originate a Route Discovery more frequently, compared with the fashions where buildings are not a component of the model.

8.4 Quantitative Parameters

The overall experiment runs have step by step isolated a particular input parameter to explore a set of distinct metrics. Particularly, the consistency tests, as well as the very simulations have led to draw a few conclusions regarding the simulation parameters.

In first instance, the analysis done in Section 8.2 underlined two fundamental issues related with the study of particular mobility patterns:

- The concentration of nodes per unit of area, is a key parameter that could compromise the simulation final results. In fact, an erroneous choice for it is likely to be the cause of unreasonable, and misleading protocol performance.
- Wireless network simulations must be performed with the awareness that an initialization of the system does not necessarily represent its typical state. Hence, a pre-simulation phase is always needed to give a chance to the system to become steady. Such a transient period of time should be studied on purpose depending upon the study being done.

In second instance, the two set of experiments suggested that:

- Fixed a pair (MM,RPM), and fixed a reasonable range where to vary the speed of movement of the mobile entities; the Dynamic Source Routing protocol (DSR) is able to reach even results in terms of throughput, regardless the particular speed. In other words, the delivery fraction does not show any drastic decline owing to the mobility degree. This holds for the few reasonable speed values considered in my runs. Important remark is that the equal throughput is achieved with a routing effort which grows linearly with the maximum velocity of movement.
- Likewise, given a pair (MM,RWP) and fixed a restricted set of simulation terrains; DSR is capable of reaching even results in terms of throughput, regardless the particular surface's size. This holds as long as the node density per unit of area is maintained constant. Once again, the equal results are achieved with a distinct routing effort proportional to the area's size. The routing overhead does not seem to

increase linearly, but rather with a tendency that looks to be exponential. The explanation lies in the fact that a wider area forces the routes to be longer. Consequence is that the routing messages have to be broadcasted more massively.

8.5 Summary

In a mobility model where the nodes are forced to walk along predefined pathways, DSR was observed to generate less control traffic in comparison with the RWP mobility pattern. Nevertheless, the throughput achieved by the two mobility patterns was observed to be equally optimal and indistinguishable.

In contrast, comparing *UMMoff* with *UMMon* has proven that effectively the radio signal propagation constraints drastically influence the performance of the routing protocol. In fact, an additional immense routing effort is required to cope with the presence of buildings. Moreover, the further overhead generated is not even enough to achieve equal results in terms of throughput.

Shortly, we can claim that the mobility pattern slightly affects the DSR performance. Contrarily, a more realistic Radio Propagation Model influences in a drastic way the behavior of the routing protocol.

Chapter 9

Conclusions

Often, the most of the existing mobility models previously taken into account by the MANET community [6, 10] were an enhancement to the trivial RWP-MM. The thesis argued that such artificial scenarios are too simplistic and too narrow in their scopes. Thus, it proposed a new pattern compound of more sophisticated mechanisms to model mobility and radio signals prediction that contribute to make the simulation realistic.

I introduced UMM, a novel model to set up an artificial urban environment to be simulated with NS2. The strength of such a model is that an experimenter can select a few input parameters to obtain the realistic city-like environment that better suits its needs. In fact, variants of UMM are easily obtainable that represent the desired topological features in terms of roads and buildings.

I modeled a simple city terrain and simulated wireless networks behavior within it through the usage of DSR protocol. The results showed that Urban Mobility itself eases the routing protocol's duty. In fact, having a constant concentration of Mobile Terminals per unit of area forces UMM to have an apparently more dense configuration in comparison with the RWP-MM. The phenomenon occurs because the roads favor a nodes clustering that contributes to increase the network density along the predefined pathways.

Additionally, the findings have clearly proven what a drastic decrease in routing performance is caused when simulation closely resembles the real world signal propagation issues. The results have shown that throughput goes down when obstructing buildings are introduced in the artificial environment. Moreover, in such a case, the protocol generates an immense amount of signaling overhead that only partially is capable of coping with the strict propagation rules assumed by *UMMon*.

Thus, we infer that the topological aspects of the area in which an ad hoc network operates are absolutely fundamental to be deemed during a network simulation. These topological aspects can only be modeled by reasonably introducing a sensible Radio Propagation Model. Furthermore, when obstacles are located in the area, some mechanisms to limit the motion must also be introduced to prevent the entities to pass through the walls. Nevertheless, it seems that the MANET community has always preferred to neglect these components of a simulation pattern. Hence, the author wants to remark the current distance from the existent simulation models (MM, RPM) and the real world situations.

My contribution is a first step to sensitize the research in the area to face with more realistic simulation models. They certainly help to draw more useful conclusions, but on the other hand they require a further computational effort to evaluate protocol performance. Although, I still believe that the benefit is worth the trouble.

There are a number of ways to integrate this initial work. In first instance, in order to retrieve more general results depending on the particular configuration of roads and buildings, a wider set of realistic environments should be investigated. In fact, cities are only one of the many possible places of action of the ad hoc networks.

Furthermore, a study which compares a number of distinct routing protocols would provide additional insights. Specifically, it would draw conclusions regarding the choice of the best suited protocol to be employed in a precisely predefined realistic terrain.

Finally, UMM could also be strengthened in terms of degree of realism by enabling the mobiles to enter the buildings, and by introducing a restricted set of diverse mobile entities. Typically, in a city several classes of users have diverse mobility peculiarities. Think of pedestrians and different types of vehicles such as cars, trucks, trains that move with different speeds and along distinct paths to obey the traffic rules.

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