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Implementation of a Testbed and a Simulation System for MANETs: Experiments and Simulations

by

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2013

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Acknowledgement

Working three years to complete my Ph.D. course was not an easy task. The support of many people was crucial and without them this thesis would be very difficult.

First, I would like to thank my adviser, Professor Leonard Barolli, for his continuous efforts and support. He was always ready to listen and to advice. He taught me how to be practical and persistent in my projects without giving up. Without his consistency and insistence, the completion of this work would be impossible.

I thank Professor Kazunori Uchida for his every-week comments and support about my research and life. I want to thank Professor Jiro Iwashige for his kind support in difficult days. With his everyday technical recommendations and advice, Dr. Makoto Ikeda was always there. Thank you Dr. Ikeda. With the support of Ms. Sawako Tsunenoki and Mrs. Hiroko Yoshida, I overpassed the tough process of document submission and institutional procedures in Japan.

A special thank goes to Professor Makoto Takizawa (Hosei University, Japan), who always supported me spiritually and gave a lot of feedback. I also thank Professor Fatos Xhafa (Technical University of Catalonia, Spain) for his long talks and innovative ideas in my research field.

My research in Fukuoka Institute of Technology was also inspired by my colleagues. I would also like to thank my colleague, Ms. Evjola Spaho next desk, for her practical advice and moral support during these three busy years. My thanks go also to Mr. Masahiro Hiyama and all students of INA Lab studying for endless hours in the laboratory, inspiring me to work harder.

Finally I would like to thank my parents, Sami and Doloreza, my brother Bernard and my sister Eriola, for supporting me with emails and skype talks. Therefore, I want to dedicate this thesis to my beloved family. Their educational support is priceless.

Abstract

A Mobile Ad hoc Network (MANET) can be defined as a collection of mobile nodes, which form a highly resource constrained network and a dynamic topology. Because of the dynamic topology, routing procedures and protocols are a key field of testing and research. In a research environment, research tools are required to test, verify and identify problems of an algorithm or protocol. These tools are classified in three major techniques: simulators, emulators and real-world testbeds. In most of research in MANET, their performance is evaluated in both quantitative and qualitative aspects. Throughput performance, routing efficiency, security and energy consumption are some of the key issues that are addressed frequently on MANETs. The future MANET technology will have to ensure a certain degree of security and scalability and provide the infrastructure for collaborative computing. In this thesis, we design and implement a testbed and a simulation system in order to analyze the performance and compare the results of different routing protocols, mobility models and other environmental parameters. In both approaches we use different models, scenarios and traffic data models. We use our simulation results to improve the experimental environment. We experimented in indoor and outdoor environment, in horizontal and vertical topologies and in linear and mesh logical topologies. We also added mobility to specific nodes. From results, we found that the mobility of nodes brings oscillations in performance and route instabilities. Using our simulation tool, we simulated different mobility patterns in different protocols. We found multi-flow traffic decreases the performance of the network. We also proposed a data replication framework based on fuzzy logic to improve QoS in MANET. From simulation results, we found that the proposed framework had a good performance. The contributions of our work are:

1. Implementation and evaluation of a MANET testbed;

2. Implementation of a simulation tool for MANETs using NS2;
3. Application of MANET testbed in real environments, considering different scenarios;
4. Evaluation of different MANET routing protocols in different scenarios;
5. Propose a new data replication framework for improving QoS in MANET;
6. Give insights about future developments and integration of MANET as an important technology of wireless communications.

The outline of the thesis is as follows. In Chapter 1, is shown the background and the motivation of the thesis. In Chapter 2, we introduce general aspects of wireless networks. We discuss wireless architectures and wireless technologies giving advantages and disadvantages of each. We give insights of MANETs in Chapter 3. We discuss issues and problems of MANETs, and describe routing protocols and their properties. In Chapter 4, we present the design and implementation of our testbed. We give details on technical settings and environment assumptions. The scenarios and the way of implementation are described in details. The simulation system is presented in Chapter 5. We give details on radio propagation models, mobility models and other parameters used in our tests. Later we show the moving scenarios and the traffic data that we used during simulations. In Chapter 6 and Chapter 7, we discuss the results of our experiments and simulations, respectively. Chapter 8 concludes the thesis, giving an insight of learned lessons and future works in this field.

Chapter 1

Introduction

1.1 Background

The increasing need of users for communications and to access information anytime and anywhere, has made wireless mobile networks become very popular. The everyday-life wireless networks are often connected to a wired network at some points, even though the users are not aware of that fact. A wired backbone infrastructure is needed, in order for these networks to access certain resources or reach other networks and devices. The case of mobile telephony shows the above mentioned need, where each mobile host connects wireless with a base station on the wired network, with one-hop radio transmissions. Whereas, Mobile Ad Hoc Networks (MANETs), communicate in a different philosophy. A MANET is a bunch of wireless mobile devices, that can create a temporary or one-purpose (Ad Hoc) network, without any support from wired network resources. The wireless devices in MANETs, from now on in this paper referred as *nodes*, create communication paths with each other via one-hop or multi-hop links, in a peer-to-peer design. Each node in between a communication path acts as a router. Thus, the nodes should be able to operate as end-to-end devices and routers. Another feature of MANETs is the nodes random mobility, which brings the creation of different routing paths as time changes. Also, the topology of the network changes continuously. Thus, the addition and deletion of nodes from the topology need to be handled.

Recently, MANETs are continuing to attract the attention for their applications in several fields, where the communication infrastructure is expensive and/or time consuming. Mobility and the absence of any fixed infrastructure make MANET very attractive for rescue operations and time-critical applications. Communications in battlefields, disaster recovery areas or in other time-critical environments are good examples of MANET usage and applications. For example, in an area affected by a disaster, the creation of a quick communication network, is very important in order for the public safety agencies and rescue teams can share critical information for the situation.

More specific MANETs, that have attracted a great amount of research interests, are Wireless Sensor Networks (WSNs) and Vehicular Ad-hoc Networks (VANETs). WSNs are MANETs consisting of sensor nodes and serve to measure some environmental parameter, and collect the information in special nodes called sinks. VANETs are MANETs with the special feature of conditional movement, modeling lanes of a road. Research for MANETs has been done usually in simulation, because in general, a simulator can give a quick and inexpensive evaluation of protocols and algorithms. However, experimentations in the real world are very important to verify the simulation results and to revise the models implemented in the simulator. A typical example of this approach has revealed many aspects of IEEE 802.11, like the gray-zones effect [1], which usually are not taken into account in standard simulators, as the well-known *ns-2* simulator.

We conducted many experiments with our MANET testbed [2,3]. We proved that while some of the Optimized Link State Routing (OLSR) problems can be solved (for instance the routing loop), this protocol still have the self-interference problem. There is an intricate inter-dependence between MAC layer and routing layer, which can lead the experimenter to misunderstand the results of the experiments. For example, the horizon is not caused only by IEEE 802.11 Distributed Coordination Function (DCF), but also by the routing protocol.

We carried out the experiments with different routing protocols such as OLSR and Better Approach to Mobile Ad-hoc Networks (BATMAN) and found that throughput of TCP was improved by reducing Link Quality Window Size (LQWS), but there were packetloss because of experimental environment and traffic interference. For TCP data flow, we got better results when the LQWS value was 10. Moreover, we found that the node join and leave operations affect more the TCP throughput and Round Trip Time (RTT) than UDP [4]. In [5], we showed that BATMAN buffering feature showed a better performance than Ad-hoc On-demand Distance Vector (AODV), by handling the communication better when routes changed dynamically.

1.2 Research Background and Related Work

In the most cases, researchers for MANETs are concentrated on specific problems of the networking stack, by trying to specifically identify and evaluate the causes of performance degradation. Many simulation results exist, in which different network layers have been evaluated. Simulation is unavoidable to analyze the scaling behavior of MANETs, which can consist of hundreds of nodes. However experiments in real-world environment are very important, as they verify simulation results and confirm the efficiency of models, protocols or algorithms implemented in the simulator.

In [6], an outdoor experimental analyze to an ad-hoc network is done to reactive protocols, such as: AODV (Ad hoc On demand Distance Vector) and DSR (Dynamic Source Routing). The authors of [7] performed experiments on an outdoor MANET, but used only non-standard proactive protocols. Other ad-hoc experiments are limited to identify MAC problems, by providing insights on the one-hop MAC dynamics as shown in [8]. A close work to this thesis is that in [9], but the authors there do not take care of the routing protocol. In [10], the disadvantage of using hysteresis routing metrics is presented through simulation and indoor measurements. The authors in [11], presented an experimental comparison of OLSR using the standard hysteresis routing metric and the Expected Transmission Count (ETX) metric in a 7 by 7 grid of closely spaced Wi-Fi nodes to obtain more realistic results.

Many testbed projects exist now around the world. One of the most similar projects which is still active on experimental analysis of ad hoc networks is that of the group at Uppsala University, which implemented a large testbed of 30 nodes [1, 12]. They presented an automatic software called APE which can set and run measurements in an ad hoc network with a particular routing protocol, i.e. AODV, OLSR, or LUNAR. The authors of the experiments suggested to use a particular metric to solve the repeatability problem caused by the movement pattern of mobile nodes. Their main objective was to understand the performance differences among different routing protocols.

The objective of this thesis is similar because it is focused on performance analysis, but with more emphasis on the methodology of analysis. For instance, evaluation here is concerned with the behavior of a particular protocol under different parameter settings.

Many researchers performed valuable research in the area of wireless multi-hop networks by computer simulations and experiments [13, 14]. Most of them are focused on throughput improvement, but they do not consider mobility [15].

In [16], the authors implemented multi-hop mesh network called Massachusetts Institute of Technology (MIT) Roofnet, which consists of about 50 nodes. They consider the impact of node density and connectivity in the network performance. The authors show that the multi-hop link is better than single-hop link in terms of throughput and connectivity. In [17], the authors analyze the performance of an outdoor ad-hoc network, of AODV and Dynamic Source Routing (DSR) [18] reactive routing protocols.

In [19], the authors perform outdoor experiments of non standard proactive protocols. Other ad-hoc experiments are limited to identify MAC problems, by providing insights on the one-hop MAC dynamics as shown in [20]. In [21], the disadvantage of using hysteresis routing metric is presented through simulation and indoor measurements.

In [22], the authors presents performance of OLSR using the standard hysteresis routing metric and the Expected Transmission Count (ETX) metric in a 7 by 7 grid of closely spaced Wi-Fi nodes to obtain more realistic results. The throughput results are effected by hop distance, similar to our previous work [23].

In [24, 25], the authors propose a dynamic probabilistic broadcasting scheme for mobile ad-hoc networks where nodes move according to different mobility models. Simulation results show that their approach outperforms the Fixed Probability Ad hoc On-demand Distance Vector (FP-AODV) and simple AODV in terms of saved rebroadcast under different mobility models. It also achieves higher saved rebroadcast and low collision as well as low number of relays than the fixed probabilistic scheme and simple AODV.

The authors of [26] evaluate the robustness of simplified mobility and radio propagation models for indoor MANET simulations. They show that common simplified mobility and radio propagation models are not robust. By analyzing their results, they cast doubt on the soundness of evaluations of MANET routing protocols based on simplified mobility and radio propagation models, and expose the urgent need for more research on realistic MANET simulation.

In [27], three metrics are recommended to construct a credible MANET simulation scenario: average shortest-path hop count, average network partitioning, and average neighbor count. The main contribution of this work is to provide researchers with models that allow them to easily construct rigorous MANET simulation scenarios.

In this thesis, we contribute in the research field as in the following:

- Implementation and evaluation of a MANET testbed;
- Implementation of a simulation tool for MANETs using NS2;
- Application of MANET testbed in real environments, considering different scenarios;
- Evaluation of different MANET routing protocols in different scenarios;
- Propose a new data replication framework for improving QoS in MANET;
- Give insights about future developments and integration of MANET as an important technology of wireless communications.

1.3 The Structure Of The Thesis

The outline of the thesis is as follows. In Chapter 1 is shown the background and the motivation of the thesis. We show some related works and our contribution to the field. In Chapter 2, we introduce general aspects of wireless networks. We discuss wireless architectures and wireless technologies giving advantages and disadvantages of each. We also compare wireless networks to wired networks, showing pros and cons for each. We give insights of MANETs in Chapter 3. We show basic functionalities of MANETs and discuss its issues and problems. We also describe routing protocols and their properties for both proactive and reactive groups. In Chapter 4, we present the design and implementation of our testbed. We give details on technical settings and environment assumptions. The scenarios and the way of implementation are described in details in three different cases. The simulation system is presented in

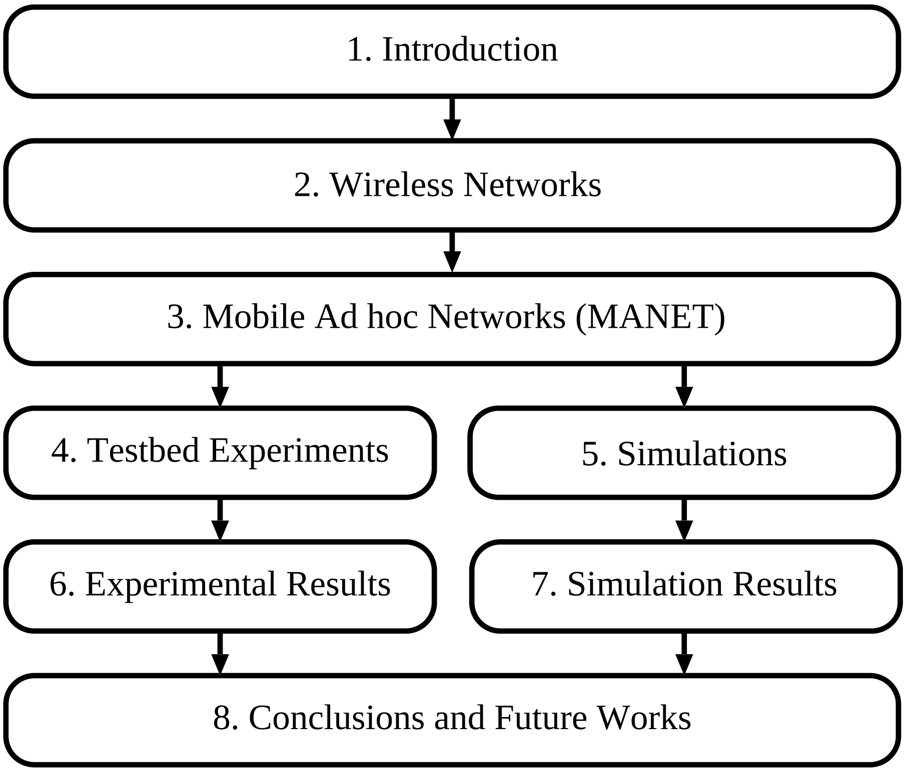

Figure 1.1: The structure of the thesis.

Chapter 5. We give details on radio propagation models, mobility models and other parameters used in our tests. We also show the moving scenarios and the traffic data type that we used during simulations. We describe in details each of the four cases that we considered in our simulations. In Chapter 6 and Chapter 7, we discuss the results of our experiments and simulations, respectively. Chapter 8 concludes the thesis, giving an insight of learned lessons and future works.

Chapter 2

Wireless Networks

2.1 Introduction

Wireless networks have evolved with great speed during the last decades and it seems like in the future this speed will keep going. A telecommunication network, in which no wires are used to create the interconnections, is referred to as Wireless Network. Since now many technologies and standards are developed using wireless communications. In this chapter, we describe some of basic concepts of wireless networks and some of their applications

2.2 Wireless Architecture

Wireless networks can be built using two network architectures: infrastructure architecture and ad hoc architecture. A simple example to make a comparison between the two is shown in Figure 2.1.

2.2.1 Infrastracture Architecture

In general, the wireless networks are used to extend wired networks in areas where it was almost impossible to install wires. Many wireless units connect wirelessly to one unit, which is wired to the wide network. This unit has a very critical role in keeping the network connected. We called this node an Access Point (AP) or Base Station (BS), meaning that each node can have access to the network only by

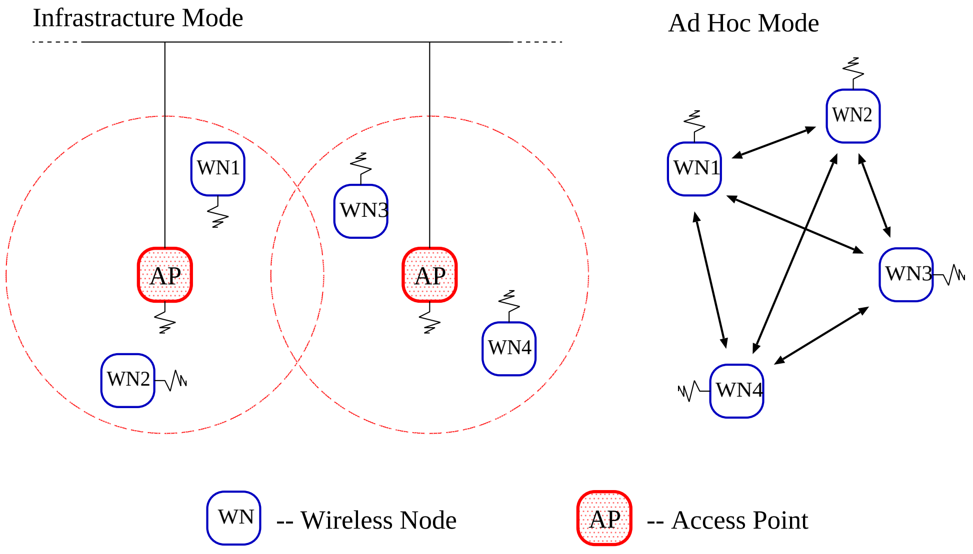

Figure 2.1: Ad-Hoc and infrastructure mode.

accessing this central node. Even though two nodes may be near each other, they both need to be connected with the AP.

APs usually transmit with more power than other units, to ensure a given coverage area. They are also responsible for coordinating access to simultaneous transmission from all units in the coverage area. It assigns transmission channels to the units. These channels can be *frequencies* (Frequency Division Multiple Access), *time slots* (Time Division Multiple Access) *orthogonal codes* (Code Division Multiple Access) or a mixture of the above mentioned methods.

In the infrastructure architecture, wireless transmissions occur only in the last hop of communication, where all units in the coverage area share the bandwidth of the wireless channel.

2.2.2 Ad Hoc Architecture

In ad hoc architecture, units create a temporary and dynamic network without any aid from wired networks. All units are independent of each other and can cooperate to maintain network connectivity. Ad hoc architecture is characterized by a random and dynamic topology and by multi-hop communication. No wired support is needed, so these networks can exist by their own.

Unlike infrastructure architecture, in ad hoc architecture units should provide multi-hop transmission by being able to forward packets for other units. This makes the units operate in both end device mode as well as router mode. The MANET work group of IETF is formed to support Ad hoc issues and improvements.

In Fig. 2.1, in infrastructure architecture of a 802.11b, even though their transmission range cover each other geographical position, nodes WN1 and WN3 are part of different infrastructures, separated by APs. Thus, they can communicate only through their respective APs. While, in Ad hoc mode, each node can communicate with every other node which is inside its transmission range. This means that Ad Hoc Networks do not need the aid of any central device. By avoiding the centralized administration of the network in ad hoc infrastructure, the “one point of failure” is also avoided.

2.3 Wireless vs. Wired

The evolution from wired networks to wireless networks has lead to some issues due to some problem-posing phenomena. These phenomena, should be addressed correctly, when deploying the communication algorithm. Three of the most problematic phenomena are discussed in following.

2.3.1 Collision

When two units in the same network try to communicate simultaneously in the same channel, collision occurs. In wired networks, switching devices are used to allow units to take turns sending packets, while in wireless networks communication is done through an antenna, which usually is omni-directional. This makes it more difficult to control the collision issue, because a single antenna can be used only for receiving or only for transmitting in a certain given time. Thus, if two units try to transmit messages to the same third party unit, this unit will not understand neither of the messages.

2.3.2 Unidirectional Links

In wired networks a link is always available from both sides communicating, being a two-way link. While, in wireless networks this situation is not always true. The units may have different antenna characteristics, the receiving and transmitting circiuts may provide different power levels, and there may be interference from other sources.

These conditions cause some links to be unidirectional, being one-way links. This means a unit should be aware of the availability of both direction links, before transmitting any signal.

2.3.3 Asymmetric Links

Another phenomena which may occur due to radio irregularities, is the asymmetric links. An asymmetric link has different network parameters for downstreaming and upstreaming (like an ADSL line). These links may cause problems if not taken into account by the communicating units.

2.4 The Wireless Channel

Communication of nodes in Ad Hoc Networks are done through wireless transceivers. Thus, the wireless channel is an important block of any model used to describe a wireless system. A more detailed description can be found in [28].

A radio channel between a transmitter unit u and a receiver unit v is established if and only if the power of the radio signal received by node v is above the sensitivity threshold. Theoretically, there exists a direct wireless link between a transmitter unit u and a receiver unit v if $P_r \geq \beta$, where P_r is the power of the signal received by v, and β denotes the sensitivity threshold. The exact value of β depends on the features of the wireless transceiver and on the communication data rate. If we increase the data rate for a given radio, the value of β will be increased. The received power P_r is affected by the power P_t used by unit u to transmit, and on the path loss, which models the wireless signal degradation with distance. Denoting with $PL(u, v)$ the path loss between units u and v, we can write:

$$P_r = \frac{P_t}{PL(u, v)}. \tag{2.1}$$

Modeling path loss is one of the most difficult tasks of the wireless system designer. The mechanisms that affect the radio signal propagation can be classified into three major categories: reflection, diffraction and scattering.

- When electromagnetic waves hit the surface of a large object (earth surface, large buildings etc.), compared to the wavelength of the propagating signal, *reflection* occurs.

- *Diffraction* occurs when there are objects with sharp edges lying on the radio path between the transmitter and the receiver.
- Sometimes several small objects, (as compared to the signal wavelength) may happen to be in between the transmitter and the receiver of the radio signal. In this case *scattering* occurs.

Taking into account these mechanisms, makes radio wave propagation an extremely complex phenomenon, which is heavily influenced by environmental factors. We will explain shortly three widely-used path loss models.

2.4.1 Free Space Propagation Model

The free space propagation model is used to describe radio signal propagation when between the transmitter and the receiver there is no obstructions, Line-Of-Sight (LOS). Denoting with $P_r(d)$ the power of the radio signal received by a node located at distance d from the transmitter, we have:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{2.2}$$

where $\mathbf{G_t}$ is the transmitter antenna gain, $\mathbf{G_r}$ is the receiver antenna gain, $\mathbf{L}$ is the system loss factor not related to propagation and λ is the wavelength in meters.

By simplifying Equation (2.2) and denoting C_f the constants, which depends only on transceiver characteristics, a more simple equation derives:

$$P_r(d) = C_f \frac{P_t}{d^2}. \tag{2.3}$$

Equation (2.3) shows the decreasing of the received power is proportional to the square of the distance d that separates the transmitter and the receiver. Combining Equation (2.3) with the sensitivity threshold, we can claim that the transmitted message can be correctly received if and only if $d \leq \sqrt{C_f P_t}$. In other words, the coverage area of a wireless node transmitting at power P_t is a disk of radius $\sqrt{C_f P_t}$ centered at the transmitter.

2.4.2 Two-Ray Ground Model

In most of the cases, the signal sent from the transmitter to the receiver follows multiple radio paths. For this reason, the free space propagation model is not

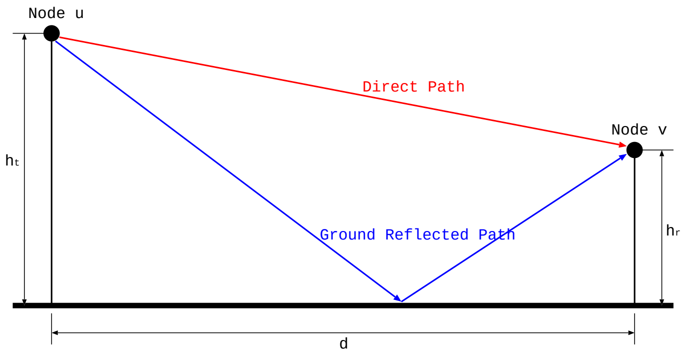

Figure 2.2: Two-ray Ground Propagation Model.

always correct. A more accurate approach to modeling the propagation of the radio signal is the two-ray ground model, which considers two propagation paths: the direct path and a ground reflected propagation path[1] between the transmitter and the receiver (see Fig. 2.2).

The radio signal sent by node u reaches node v through the direct path, and through a ground reflected path. The received power at distance d, in the two-ray ground propagation model is given by the following formula:

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

where $\mathbf{h_t}$ is the transmitter antenna height and $\mathbf{h_r}$ is the receiver antenna height.

If the sender and the receiver are relatively far from each other ($d \gg \sqrt{h_t h_r}$), and denoting C_t the constants, which depends only on transceiver characteristics, the following simplified formula can be written:

$$P_r(d) = C_t \frac{P_t}{d^4}. \tag{2.5}$$

In Equation (2.5), it can be easily noticed that the decreasing of radio signal power is in proportional to the distance between nodes raised to the fourth power, instead of to the square, in the Free Space model. Combining Equation (2.5) with the sensitivity threshold, we can claim that the transmitted message can be correctly received if and only if $d \leq \sqrt[4]{C_t P_t}$. In other words, the coverage area of a wireless node transmitting at power P_t is a disk of radius $\sqrt[4]{C_t P_t}$ centered at the transmitter.

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[1] This is not to be misinterpreted as Multi-path Fading.

Table 2.1: Values of the path loss exponent in different environments.

Environment	α
Open Space	2
Urban Area	$2.7 - 3.5$
Indoor LOS	$1.6 - 1.8$
Indoor no LOS	$4 - 6$

2.4.3 Shadowing Model

The shadowing (log-distance) model has been derived combining analytical and empirical methods. Empirical methods are based on field measurements and statistical calculation on the experimental data. This model, which can be seen as a mixture of both the free space and the two-ray ground models, indicates that the average shadowing path loss is proportional to the separation distance d raised to a certain exponent α, which is called *the path loss exponent*, or *distance-power gradient.*

$$P_r(d) \approx \frac{P_t}{d^\alpha} \tag{2.6}$$

From Equation (2.6), we can claim that the radio coverage region in this model is a disk of radius proportional to $\sqrt[\alpha]{P_t}$ centered at the transmitting node. The value of α depends on the environmental conditions, and it has been experimentally evaluated in many scenarios. The author of [28], provides us with some values of α. Tab. 2.1 summarizes some of these values.

2.5 Wireless Technologies

2.5.1 Wi-Fi

Wi-Fi (Wireless Fidelity) service is defined from the IEEE (Institute of Electrical and Electronics Engineering), by a set of standards and specifications, named IEEE 802.11. The original 802.11 standard (no suffix) was released in 1997. The 802.11b standard provides additional specifications for wireless Ethernet networks. While as the IEEE 802.11a standard describes wireless networks that operate at higher speeds, other 802.11 radio networking standards are also available.

The most popular specifications today are 802.11a, 802.11b, and 802.11g. They are the de facto standards used by the wireless Ethernet LAN that is installed in offices, on campus and in most home networks. The 802.11n standard will replace both 802.11b and 802.11g. It is faster, more secure, and more reliable. The older standards will still be supported, by the new Wi-Fi equipment.

2.5.2 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) is a metropolitan area network service that usually uses base stations which can provide service to users within a 30-mile radius. WiMAX service providers use licensed operating frequencies between 2 GHz and 11 GHz in which a WiMAX link can transfer data at up to 70Mbps. When many users share a single WiMAX tower and base station, the signal quality deteriorates. WiMAX is an independent radio system that is designed to either supplement or replace the existing broadband Internet distribution systems. In practice, WiMAX competes with both 3G wireless services and with Internet service providers that distribute Internet access to fixed locations through telephone lines and cable television utilities. Subscribers to a WiMAX service usually use either a wired LAN or Wi-Fi to distribute the network within their buildings.

2.5.3 Bluetooth

Bluetooth uses radio signals to replace the wires and cables that connect a computer or a mobile telephone to peripheral devices, such as a keyboard, a mouse, or a set of speakers. The Bluetooth can also be used to transfer data between a computer and a mobile telephone, smartphone, BlackBerry, or other PDAs (Personal Digital Assistant). Bluetooth moves among 79 different frequencies 1,600 times per second in the same unlicensed 2.4 GHz range as 802.11b and 802.11g Wi-Fi services. Bluetooth is not very practical for connecting a computer to the Internet because it's slow (the maximum data transfer rate is only about 3Mbps), and it has a very limited signal range (maximum 100 meters with LOS). In order to prevent interference between Bluetooth and Wi-Fi signals, many computers that use both technologies (including the widely used Intel Centrino chip set) coordinate the two services. This coordinated operation is slightly slower than either service operating alone, but the difference is insignificant.

2.5.4 4G Cellular Networks

4G is being developed to accommodate the QoS and rate requirements set by further development of existing 3G applications like WBA, Multimedia Messaging Service (MMS), video chat, mobile TV, but also new services like HDTV content, minimal services like voice and data, and other services that utilize bandwidth. It may be allowed roaming with WLANs, and be combined with digital video broadcasting systems.

According to the members of the 4G working group, the infrastructure and the terminals of 4G will have almost all the standards from 2G to 4G implemented. Although legacy systems are in place to adopt existing users, the infrastructure for 4G will be only packet-based (all-IP). Some proposals suggest having an open Internet platform. Technologies considered to be early 4G include: Flash-OFDM, the 802.16e mobile version of WiMax, and HC-SDMA.

2.5.5 MANETs

The rapid deployment of a mobile user, is going to be present in the next generation of wireless systems. Some real applications include establishing survivable, dynamic communication for emergency/rescue operations, disaster relief efforts, and military networks. Such network scenarios cannot rely on centralized and organized connectivity.

A MANET is an autonomous group of mobile terminals that communicate with each other over wireless links. Thee network topology may change quickly and randomly over time, because terminals are mobile. The network is decentralized, and all network activity such as, discovering the topology and delivering messages must be executed by the nodes themselves. For this reason, routing functionality will be incorporated into these mobile nodes.

The set of applications for MANETs is wide, ranging from small, static networks to large, highly dynamic networks. Designing the protocols for these networks, in order to determine network organization, link scheduling, and routing is a very complex issue. However, determining viable routing paths and delivering messages in a decentralized environment where network topology fluctuates is not a well-defined problem. While the shortest path (based on a given cost function) from a source to a destination in a static network is usually the optimal route, this idea is not easily extended to MANETs. Factors such as variable wireless link quality, propagation path loss, multiuser interference, power expended, and topological changes, are relevant issues. The network should be able to adaptively alter the routing paths to alleviate any of these effects.

Chapter 3

MANET

MANETs are formed by several wireless terminals, which can be mobile or semi-mobile. These terminals, or nodes, do not have a pre-established infrastructure, meaning that they create a fast and temporary network whenever they are deployed in an environment. Each of the nodes has a wireless interface and communicate with each other over radio or infrared links in a Peer-to-Peer (P2P) design. Examples of MANET nodes are, notebooks and PDAs used widely now everywhere. In general, nodes in MANETs are mobile, and their movement is random and difficult to be modeled, but according to mankind lifestyle, we always try to implement similar models to what happens in real life. Some nodes can be static as well. they can be used to interconnect the Ad Hoc Network to another network or the Internet, or the user simply is sitting with his notebook and using network resources.

MANETs need to have implemented some mechanisms as follows.

- If provides inter-networking, an Internet access mechanisms is needed.
- Self configuring networks requires an address allocation mechanism.
- Mechanism to detect and act on merging of existing networks.
- Security mechanisms.
- Nodes must be able to relay traffic since communicating nodes might be out of range.
- Multi-hop operation requires a routing mechanism designed for mobile nodes.

3.1 MANETs Usage and Applications

Recently, MANETs have drawn too much attention as a research field. As a result of this considerable research activity, the basic mechanisms that enable wireless ad hoc communication have been designed and standardized. The future seems to be bright for MANETs, which will take advantage of its most distinguishable characteristics, mobility and multi-hop, to take the place of wired multi-hop backbones, because they are so easy and inexpensive to be implemented, even in areas where infrastructure is impossible to appear.

MANETs are the networks of the future in many applications. By using ad hoc philosophy, each user (node) gets in and out of the network whenever it finds it convenient, without being noticed by other users. This means, that even in the worst case of an unexpected failure of a node, the network is still up. This brings a lot of advantages in using MANETs in many applications. Some of the most common application fields, in which MANETs have great success are:

Military Scenarios : In battlefield it is preferable to make a very quick deployment of information networks, and without the use of any infrastructure or centralized administration.

Sensor Networks : WSNs are a very interesting application of MANETs, where a bunch of sensors, equipped with a radio antenna, are able to send useful collected information to where we want, or compute aggregate values of the parameters sensed in the environment.

Students Campus : That is a very useful application, for every environment where density of wireless terminals is high enough to cover the intended area.

Conferences : The property of quick-deployment and mobility, make MANETs an adaptive tool to keep everyone connected in the conferences.

OLPC : One Laptop Per Child project [29] is being implemented in developing countries, where sometimes there is no proper infrastructure for all laptops to stay connected. MANETs provide the solution here.

3.2 MANETs Challenges

Even though the technology for MANETs exists and is developing, applications based on the ad hoc networking paradigm are almost completely lacking. This is because many of the challenges to be faced for a practical implementation of ad hoc network services are still to be solved.

Energy Conservation: Units in MANETs are typically battery equipped. One of the primary design goals is to use limited amount of energy as efficiently as possible.

Unstructured and Changeable Network Topology: Since the network nodes can, in principle, be arbitrarily placed in a certain region and are typically mobile, the topology of the graph that represents the wireless communication links between the nodes is usually unstructured. Furthermore, the network topology may vary with time, because of node mobility or failure. In these conditions, optimizing the performance of ad hoc network protocols is a very difficult task.

Low-quality Communications: Communication on a wireless channel is, in general, much less reliable than in a wired channel. Furthermore, the quality of communication is influenced by environmental factors (weather conditions, presence of obstacles, interference with other radio networks, etc.), which are time varying. Thus, applications for MANETs should be resilient to dramatically varying link conditions, tolerating also non-negligible off-service time intervals of the wireless link.

Resource-constrained Computation: MANETs are characterized by low resource availability. In particular, energy and network bandwidth are available in very limited amounts as compared to more traditional network paradigms. Protocols for MANETs must strive to provide the desired performance level in spite of the few available resources.

Scalability: In some MANET scenarios, the network can be composed of hundreds or of nodes. This means that protocols for MANETs must be able to operate efficiently in the presence of a very large number of nodes also.

In case of MANETs used for "ubiquitous" networking, the following issues must also be addressed.

Interoperability: In the "ubiquitous" networking scenario data can travel through the most diverse type of networks: ad hoc, cellular, satellite, wireless LAN, PSTN, Internet, and so on. Ideally, the user should smoothly switch from one network to the other without interrupting his applications. Implementing this sort of 'network handoff' is a very challenging task.

Definition of Feasible Business Models: Today, accounting in wireless networks (cellular, and commercial wireless Internet access) is done at the base station, that is, using a centralized infrastructure. Furthermore, roaming is allowed only within networks of the same type (e.g. cell phone roaming when the user is in a foreign country). In the ubiquitous scenario, it is still not clear which infrastructure should perform billing and which rules should be used to regulate roaming between different types of networks.

Stimulate Cooperation Between Nodes: When designing a certain network protocol, it is usually assumed that all the nodes in the network voluntarily participate in the protocol execution. In some MANET application scenarios, network nodes are owned by different authorities (private users, professionals, profit and/or nonprofit organizations, and so on), and voluntary participation in the protocol execution cannot be taken for granted. Thus, network nodes must be somehow stimulated to behave according to the protocol specifications.

3.3 Routing in MANETs

There are many reasons why mobile ad hoc networking is being researched by many organizations and institutes around the globe. The dynamic nature and the lack of infrastructure of these networks, is asking more and more implementation of networking strategies and paradigms, to be able to provide efficient communication. Along with that, the variety of applications of MANETs in different scenarios, have made research interests growing in this field.

In MANETs, the well-known TCP/IP structure is used by the nodes to make the communication happen. However, due to their mobility and low resource capacities, for the MANETs to function efficiently, one should modify each layer of TCP/IP stack. Thus, many routing protocols and algorithms are developed and proposed, and each author of each of the protocols, claims improvements over existing approaches, for specific network scenarios. For a routing protocol to function efficiently in MANETs, it should have the following features:

- Self starting and self organizing,
- Multi-hop, loop-free paths,
- Dynamic topology maintenance,
- Rapid convergence,
- Minimal network traffic overhead,
- Scalable to large networks.

The routing protocols are separated into two main categories:

1. Reactive MANET Routing Protocols (RMRP).
2. Proactive MANET Routing Protocols (PMRP).

Adaptive or Hybrid Routing Protocols are also available, but these protocols use features of both RMRP and PMRP, mixed together. In this section, we give a short description of routing protocol categories, some routing protocols for each category and some features of each. A review of these routing protocols when used in large scalable MANETs can be found in [30].

3.3.1 Proactive Routing

Proactive routing protocols function in a way that each node maintains routing information to every other node (or nodes located in a specific part) in the network, in one or many tables or lists. This means that all routes are maintained during all the time of network operation. Topology changes, which is very frequent in MANETs brings a lot of traffic control information exchanged between nodes. PMRPs differ among each other in the way each node updates and detects the routing information, and the number of tables used to keep different types of information. Although the routes in PMRPs are always available, constant overhead is created by control traffic. Some of the most popular PMRPs are: Destination Sequenced Distance Vector (DSDV), Fisheye State Routing (FSR) and Optimized Link State Routing (OLSR). We will present OLSR and BATMAN protocols in following.

3.3.1.1 Optimized Link State Routing (RFC3626)

The OLSR protocol for mobile ad hoc networks is a PMRP. It is developed as a MANET compatible version of the classical link state algorithm. OLSR source code is available online, and it can be found in `http://www.olsr.org`. The new concept OLSR brought to MANET, is MultiPoint Relaying (MPR). Lets explain in short details the functioning of OLSR. The OLSR protocol can be divided in to three main modules:

- Neighbor/link sensing,
- Optimized flooding/forwarding (MPR),
- Link-State messaging and route calculation.

Neighbor and link sensing is realized by sending HELLO packets. All nodes transmit HELLO packets at a given interval. The 3-way handshake performed by two neighbors creates link information for both nodes. The HELLO packets also contain information about all active neighbors, so each node knows about 1-hop and 2-hop neighbors. Topology Control (TC) packets are also exchanged between neighbors to keep track of topology changing.

If OLSR would make a regular flooding of HELLO packets, too much unwanted traffic would flow on the network. The optimization of OLSR consists on exactly decreasing this traffic overhead. This is done by introducing the new concept of MPR. Node X choses a set $mpr(X)$ of MPRs from its 1-hop neighbors, so that all 2-hop neoghbors of node X is reached via the set $mpr(X)$. Flooding and forwarding is thus optimized in this way. A node recieveing a packet from node X, forwards or floods it, only if the node itself is in the set $mpr(X)$ of MPRs of node X. Fig. 3.1 shows how node X handles the selection of MPRs to cover all its 2-hop neighbors. Another optimizization consists on MPRs choosing to report only links between itself and its MPR selectors[1]. So, partial information is distributed into the network.

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[1] Node B selects node A, as one of its MPRs, at the same time also node C selects A as one of its MPRs. Node B and node C are both MPR selectors of node A.

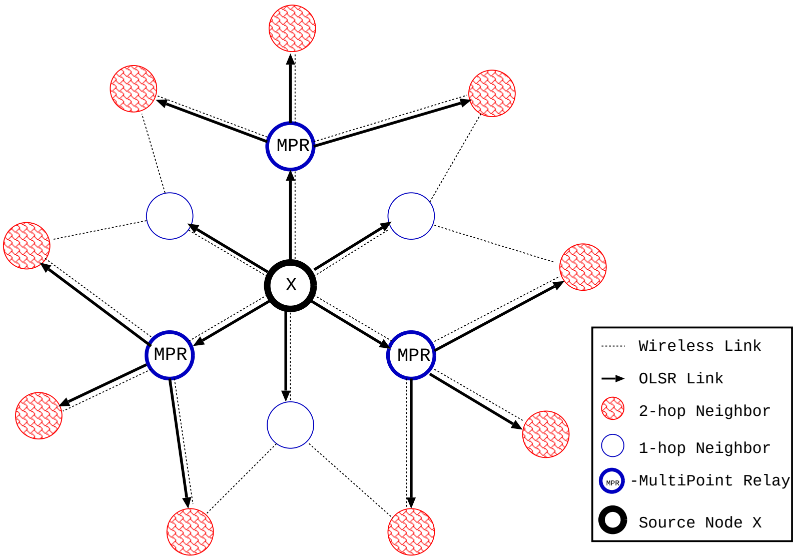

Figure 3.1: MPRs selection, reaching all 2-hop neighbors

An OLSR node, has one routing table, one neighbor table and one topology table. The routing table consists of 4 entries: destination address, next hop address, number of hops to destination and local interface address. The information of the routing table is acquired from TC messages (topological set) and HELLO messages (local link information). Changes occurring in both topology and local neighbors cause the routing table to be updated[2]. The routing table is changed if one of the following happens.

- Neighbor link appear or disappear,
- Two-hops neighbor is created or removed,
- Topological link is appeared or lost,
- The multiple interface association information changes.

These leads to a call of *Route Calculation* function, usually performed by the shortest path algorithm. After recalculating the routes, the routing table is updated with the new information. Oldest versions of *olsrd*, calculate the shortest path with the hop-count as a target metric. Latest *olsrd* software have been equipped with Link Quality (LQ) extension, which uses the packetloss rate as target metric. This metric is called Expected Transmission Count (ETX) and is defined as $ETX(i) =$

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[2] As OLSR is a proactive protocol, table is updated for every node changing in the network.

$1/(NI(i) * LQI(i))$, where $NI(i)$ is the packet arrival rate seen by a node on the i-th link during the window W and $LQI(i)$ is the estimation of the packet arrival rate seen by its neighbor on the same link. This LQ extension enhances the packet delivery ratio in comparison with the old technique. Authors in [31] have found the optimal value of LQWS (Link Quality Window Size) for TCP flow, to be exactly 10. In [32] can be found the RFC3626 document for more detailed descriptions.

Anyway, the OLSR protocol is not implemented in practical scenarios. Routing tables taking a long time to build, routing loops and flapping routes are some of several issues that OLSR shows. A new routing protocol started to be developed, in order to overcome these issues. This new protocol will be described in the following.

3.3.1.2 Better Approach To MANET (BATMAN)

BATMAN is introduced as a better approach to solve these issues of OLSR. In BATMAN there is no dissemination of topology. Nodes execute the following operations:

1. Send periodic messages, called OGMs (OriGinator Messages). These OGMs contain 4 fields of data: the IP address of the originator, the IP address of the forwarding node, a TTL value and a sequence number (SQ), consisting of 52 bytes, in total.

2. Check the best one-hop neighbor for every destination in the network, by building a ranking table.

3. Rebroadcast the OGMs received from the best one-hop neighbor, or from the originator itself.

The timer in BATMAN is used for sending OGMs. The bi-directionality of links is checked using the SQ of OGM. If the SQ of and OGM received from a particular node falls within a certain range, the corresponding link is considered bi-directional. For example, suppose that in a time interval T, the node A sends T_r messages, where T_r is the rate of OGM messages. The neighbors of A will re-broadcast the OGMs of A and also other node's OGMs. When A receives some OGMs from a neighbor node B, if the last received OGM from B has a SQ less or equal to T_r, then B is considered bi-directional, otherwise it is considered unidirectional. Bi-directional links are used for the ranking procedure. The quantity T_r is called bidirectional sequence number range. The ranking procedure is the same as the link quality extension of OLSR. In few words, every node ranks its neighboring nodes by counting the total received OGMs from them. The ranking procedure is performed on OriGinator (OG) basis. Initially, for every OG, every node stores a variable called Neighbor Ranking Sequence Frame (NBRF), which is upper bounded by a particular value called ranking sequence number range. Whenever a new OGM is being received via a bi-directional link, the receiving node executes the following steps.

1. If the sequence number of the OGM is less than the corresponding NBRF, then drop the packet.
2. Otherwise, update the $NBRF = SQ(OGM)$ in the rank table.
3. If $SQ(OGM)$ is received for the first time, store OGM in a new row of the rank table.
4. Otherwise, increment by one the OGM count or make ranking for this OGM.

Finally, the ranking procedures select as the best one-hop neighbor the one which has the highest rank in the ranking table. This feature eliminates routing loops because no global topology information are flooded, the self-interference due to data traffic can cause oscillations in the throughput as we will see in our experiments. Let us note that the same OGM packet is used for: link sensing, neighbor discovery, bi-directional link validation and flooding mechanism. Other details on BATMAN can be found in [33, 34]

3.3.2 Reactive Routing

In contrary with PMRPs, in RMRPs, routes are determined and maintained each time nodes require them to send data to a destination. In this category of routing protocols, the main control overhead is the route discovery traffic. Route discovery is done by flooding a route request packet in the network. When destination (or some node which has information about destination) is reached, a route reply packet is sent back via *link reversal*, or via *flooding* to probably find a better route. Reactive protocols can be classified into two categories: hop-by-hop routing and source routing.

In Hop-by-hop Routing, data packet headers consist only of the destination address and the next hop address. Thus, data packets are routed independently by each node, based on local information, making routes adaptable to dynamically changing topology in MANETs. In this strategy, each node should have to maintain information about all active routes, and stay updated with all its neighbors. Although this is a disadvantage in MANETs, in this scenario topology information is fresher so we have better routes.

In Source Routed on-demand protocols each data packet is told the complete route from source to destination. Intermediate nodes, route these packets according to the information kept in the header of each packet. Thus, they do not need to maintain fresh routing information for each active route. They also do not need to maintain neighbor connectivity. In large networks source routing protocols do not scale well due to the added route overhead by bigger headers, and the increase of route failure probability (more nodes in a route).

RMRPs are designed to lower the overhead in proactive ones. Thus the main advantage of reactive routing is that, the bandwidth is used only when needed to find a route. The process of finding a route starts with a flooding and this usually brings initial delays. Its worth to mention some well-known RMRPs: Ad hoc On-demand Distance Vector (AODV), Dynamic Source Routing (DSR) and Temporally Ordered Routing Algorithm (TORA). We will describe AODV in following.

3.3.2.1 Ad hoc On-Demand Distance Vector (RFC 3561)

AODV is one of the most popular reactive routing protocol for MANETs. Lets see how this routing protocols works in a general view. For most detailed description see [35].

As a reactive (on demand) protocol, when a node wants to transmit data, it first starts a route discovery process, by flooding a RREQ (Route Request) packet. The RREQ packet are forwarded by all the nodes by which it is received, until the destination is found. On the way to destination, the RREQ informs all the intermediate nodes about a route to the source. When the RREQ reaches the destination, destination sends a Route Reply (RREP) packet which follows the reverse path discovered by RREQ. This informs all intermediate nodes about a route to the destination node. After RREQ and RREP are delivered to their destination, each intermediate node on the route knows what node to forward data packets in order to reach source or destination. Thus data packets do not need to carry addresses of all intermediate nodes in the route. It just carries the address of the destination node, decreasing noticeably routing overheads.

A third kind of routing message, called route error (RERR), allows nodes to notify errors, for example, because a previous neighbor has moved and is no longer reachable. If the route is not active (i.e., there is no data traffic flowing through it), all routing information expires after a timeout and is removed from the routing table.

AODV is based on DSDV and DSR algorithms. The best advantage to DSR and DSDV is that in AODV, packets being sent (the RREP packet also) carry only the address of the destination and not the addresses of all the intermediate nodes to make the delivery. This lowers routing overheads. In AODV the route discovery process may last for a long time, or it can be repeated several times, due to potential failures during the process. This introduces extra delays, and consumes more bandwidth as the size of the network increases.

3.3.3 Adaptive and Hybrid Routing Protocols

Proactive and reactive routing protocols have both its pros and cons. Thinking to get the best possible approach for a routing strategy, hybrid routing protocols appeared as trying to use the best features of both proactive and reactive. These protocols are designed to be scalable to large network. The whole network is separated in hierarchical regions, usually geographical. Some nodes are grouped trees, some trees or clusters, some clusters are grouped in a domain, and so on. Nodes within a region stay updated proactively, while to send data to a node in another region, route discovery process starts reactively. This strategy, lowers the route discovery overhead and supports very good scalability to larger networks.

3.4 MANET Research Tools

A collection of wireless mobile hosts that can dynamically establish a temporary network without any aid from fixed infrastructure is known as a MANET. These hosts can move in different directions with different speeds. MANET are found very useful in real applications such as time-lacking implementations and indoor environments.

A lot of research for MANETs has been done in simulation, because in general, a simulator can give a quick and inexpensive evaluation of protocols and algorithms. Emulation also is a good tool for research in MANETs. Hardware and simulation software components are mixed together, to create an emulation system. However, experimentation in the real world are very important to verify the simulation or emulation results and to revise the models implemented.

One of the most discussed models in literature is the mobility model. There are a lot of mobility models, which can be used in simulations and emulations, for testing MANETs. On the other hand, mobility models for real world experiments are more complicated as they require more cost, more time and/or more people. They can be implemented by people carrying nodes and walking around, or cars driving around, or even robots. In this chapter, we will make a survey on MANETs testbeds and how they implement mobility model.

3.4.1 Evaluation Techniques

In a research environment, research tools are required to test, verify and identify problems of an algorithm or protocol. These tools are classified in three major techniques: simulators, emulators and real-world testbeds. We will describe them shortly in the following.

3.4.1.1 Simulations

A simulation system consists of many assumptions and artificial modeling, in order to reach a certain realistic degree. However, these assumptions and modeling can have errors and in some cases, some realistic effects are not even considered, e.g. gray zones effect [1] are not considered in the well-known simulator *ns-2*. In the early phases of the development of a MANET algorithm or protocol, usually after the analytical modeling, simulations can give a quick and inexpensive result regarding the theoretical performance. Moreover, we can keep unchanged the simulated conditions and parameters and run the simulations as many times as we want.

3.4.1.2 Emulators

With a higher degree of realism than simulators, emulators can still control the repeatability of tests and use real hardware combined with simulation software, to conduct experiments in controlled conditions. They use artificial assumptions which are sometimes unrealistic. Emulators can be divided into physical layer emulators and MAC layer emulators. Physical layer emulators, e.g. EWANT [36], use the attenuation of the radio signal to emulate movement or obstacles. MAC layer emulators use MAC filter tools, e.g. Dummynet [37], to decide network topology and emulate mobility. Emulators have higher costs than simulators because they use real hardware.

3.4.1.3 Real-World Testbeds

Real-world testbeds have the higher level of realism because they are not based on assumptions about the experimental conditions. In testbeds, when mobility is present, the node changes its geographical location, which can have different effects on the performance. Testbeds are usually used on the final stages of the development of an algorithm or protocol. Simulation and emulation systems can make assumptions based on experimental results provided by testbeds. However, real-world testbed implementations have higher costs for hardware software and working hours. Also, the repeatability of tests in a testbed is a complicated and costly task.

3.4.2 Mobility in MANETs

With the growing applications, services and technologies of the Internet, nowadays users apart from using wireless devices, most of them are on the move for most of time. Also in MANET, Wireless Sensor Networks (WSNs) or Vehicular Adhoc Networks (VANETs), mobility is a very important feature. When it comes to testing these networks, using the tools explained in Section 3.4.1, a researcher chooses the pattern of movement of the nodes during the evaluation time. This pattern is defined as a mobility model, and in simulations there are a lot of mobility models proposed and used. In [38], the authors present a survey on mobility models and they classify them in:

Entity Mobility Models: All nodes move independently from each other.

Group Mobility Models: Nodes movement is dependent from other nodes in the network.

Mobility models in reality derive logically from different aspects of life and we can classify them in the following categories. A mobility pattern can be a mixing of all of the following.

Biology Related Mobility Models: The movement of nodes are similar to real biological species (insects, birds, fish, animals).

Activity Related Mobility Models: Different human activities, as sports, leisure etc., create different mobility patterns.

Environment Related Mobility Models: The moving pattern in cities is different from that on an open field and highways. Mobility models driven by environment are used a lot in research recently.

Random Mobility Models: These models are mostly used in simulations, when mobility is not a specific requirement. Nodes choose random directions, random destinations, random speed etc, moving in a specific area.

Considering a MANET testbed, the implementation of a mobility model is not a simple task. We will discuss some experimental systems and the mobility they used in the following section.

3.4.3 Real Testbeds with Mobility

Implementing mobility in a real-world testbed has encountered a lot of difficulties and tasks. Recently there are a lot of testbeds running in universities or research institutes. Some of them did not even consider mobility [39]. We show the characteristics of the testbeds in Table 3.1 and will describe some of them in the following, concentrating on the implementation of mobility.

In [40], the authors created a testbed for indoor and outdoor experimentations. In indoor environment, they used horizontal and vertical topologies, and implemented mobility by people carrying or pushing the wireless nodes. They used AODV, OLSR and BATMAN routing protocols and measured performance by investigating many metrics. An interesting finding, which is different from what expected, is that TCP transmission has a better performance than UDP transmission.

The authors of [13], introduce their APE testbed consisting of 37 nodes. Mobility is implemented by people carrying laptops and walking around the testing indoor and outdoor area, following the instructions on the screen. They conducted many

Table 3.1: Testbeds characteristics.

Testbed	Environment	Network Size	Indoor Outdoor	Mobility Tool	Mobility Model
Barolli et al. [40]	Real environment No assumptions	7 nodes	Both	Office chairs pushed by people	Environment related, entity mobility
APE [13]	Real environment No assumptions	37 nodes	Both	Carried by people	Environment related, group mobility
Maltz et al. [42]	Real environment No assumptions	8 nodes	Outdoor	By cars driven around the area	Environment related, entity mobility
Gray et al. [43]	Real environment No assumptions	33(40) nodes	Both	Carried by people	Random, entity mobility
TrueMobile [41]	Real environment No assumptions	16 nodes	Indoor	Robots	Random, entity mobility
ORBIT [44]	Real environment Emulates mobility	100 nodes	Both	Emulated	Sudden changes

experiments using group mobility model, which is rarely found in real world experiments. Making experiments with AODV and OLSR, they concluded that using on screen instructions has resulted in a good way to reproduce moving patterns. However, one can use robots, like in [41] instead of people to get a better reproductivity of moving patterns.

The testbed described in Maltz et al. [42], consists of six mobile nodes and two static ones. The experiments are ran outdoors and the authors use DSR protocol. They use a GPS location information system while driving nodes around the area by cars. Five moving nodes move around a given route at different speed and another moving node moves in and out of network at certain times. Exact location information resulted in a good approach to reveal that in unexpected areas the performance became lower. GPS receivers are also used in [43].

In [43], the authors used up to 33 nodes to generate different scenarios and experiments. They conducted outdoor, indoor and simulation testings. They verified that for outdoor scenarios, simulations can be a close approach for predicting performance. However, indoor experiments' results change a lot from simulation results.

Another approach to create mobility is by artificially differing parts of the network condition, making it looks like the topology is changing. In [44], the authors have created ORBIT testbed, which consists of over 100 nodes. They run experiments of different network size, indoor or outdoor, and also different moving scenarios. Mobility is realized using MAC filtering techniques, redirecting traffic to other nodes.

3.4.4 Discussion

Observing the experiences of testbed implementers, first of all we would like to mention that, building a testbed with mobility needs hard work and endurance. We did not talk about the beginning of implementation as it is not in the scope of our work.

When planning to implement a mobility model in a testbed, the first important thing that should be taken care about is what effects can this mobility pattern have on other research or real applications. It can be an environment-related, activity-related, entity or group mobility model. After deciding the moving pattern, the next problem is how to make real devices move in your experimental area, in order to be able to repeat the same movement. Driving cars [42], pushing chairs [40] or even carrying devices and walking around following on-screen instructions [13] are preferred ways of completing this task. Using automated movable robots is a more efficient technique. However this has a higher cost on each robot used. Another way of implementing mobility is emulation [44]. This method is cheaper but make unrealistic assumptions, by changing topology conditions without physically moving the nodes.

When nodes are mobile, we would like to check the position of every node at a given time of the experiment, after some months or years to verify the results. Some used methods consist of GPS receivers [42], security cameras [41], or using the relative Radio Signal Strength (RSS) to compute the location of nodes.

The experiences of other testbed builders have have good insights on building your own testbed. Another benefit we can get from the experiences of a testbed, is the use of settings in our simulation systems. As proved in [13], a simulation system can have similar results to outdoor experiments, which will help us verify our conclusions.

In this paper, we described shortly the evaluation techniques of algorithms and protocols. We also present an overview of mobility models and showed some real testbeds with mobility, implemented in the world. We make some conclusions on our work in the following.

- When using people to make the movement of the nodes, the on-screen instructions are a good way to recreate the moving patterns. Robots, on the other hand, are more precise, but the cost per node increases.

- Monitoring location and time synchronization is a difficult task, but it results in finding unpredictable effects,when nodes are mobile. It can also be used for future reference to the experiments.

- Simulation systems can give approximate results for experiments, while for indoor environments there are unpredicted results. Thus, testbed experiments give a lot of feedback to make assumptions regarding the simulation systems.

Chapter 4

Testbed Implementation and Experimental Scenarios

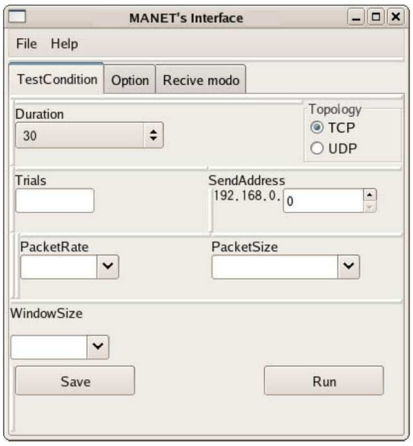
4.1 Testbed Design and Implementation

4.1.1 Description

We conducted our experiments in the stairs environment in our five-floor departmental building and in the outdoor bridges connecting our department building with other buildings in our university. The testbed consists of five laptops. The machines operate on Ubuntu Linux with kernel 2.6.28 suitably modified in order to support the wireless cards. The lynksys wireless network cards (Model: WUSB54G ver. 4) are usb-based cards with an external antenna of 2dBi gain, transmitting power of 16+/-1dBm and receiving sensitivity of -80dBm. We verified that the external antenna improves the quality of the first hop link, which is the link connecting the ad-hoc network. The driver can be downloaded from the web site [45, 46].

In our testbed, we have two systematic traffic sources we could not eliminate: the control traffic and the other wireless APs interspersed within the campus. The control traffic is due to the `ssh` program, which is used to remotely start and control the measurement software on the source node. The other traffic source brings interferences occupying the available bandwidth, which is typical in an academic scenario.

To generate the traffic between nodes, we used Distributed Internet Traffic Generator (D-ITG) software, which is an Open Source Traffic Generator [47]. With


Duration: 30

Topology: ● TCP ○ UDP

SendAddress: 192.168.0. 0

Figure 4.1: Testbed interface.

D-ITG, one could send different types of traffic from one node to another. After finishing the transmission, D-ITG offers decoding tools to get information about network metrics along the whole transmission duration.

4.1.2 Testbed Interface

Uppon the first implementation of the testbed, all the parameters settings and editing were done by using command lines of bash shell (terminal), which resulted in many misprints and the experiments were repeated many times. In order to make the experiments easier, we implemented a Graphical User Interface (GUI) interface. We used wxWidgets tool and each operation is implemented by Perl language. wxWidgets is a cross-platform GUI and tools library for GTK, MS Windows and Mac OS.

We implemented many parameters in the interface such as transmission duration, number of trials, source address, destination address, packet rate, packet size and topology setting function. We can save the data for these parameters in a text file and can manage in a better way the experimental conditions. Moreover, we implemented collection function of experimental data in order to make easier the experimenter's work. A screen-shot of the interface is shown in Fig. 4.1.

4.1.3 Testbed Environment

Our testbed provides an experimental platform for evaluating protocols and algorithms using realistic parameters. In this testbed, we can implement different topology scenarios and analyze different routing protocols considering different metrics. In this work, we take the following considerations.

- The experiments are conducted in indoor and outdoor environments inside our university campus.
- We analyzed our network for many experimental scenarios, such as static scenarios, where all nodes are static and moving scenarios, where source and destination nodes, respectively, are mobile.
- In moving scenarios, the mobile nodes move at regular speed and when they arrive at turning points, they stop for about three seconds.
- We discuss the effect of multi-hop and mobility using OLSR and BATMAN routing protocols.

4.2 Experimental Scenarios

4.2.1 Case 1: Indoor Stairs

We implemented this scenario in the stairs environment of our five-floor academic building. A snapshot of nodes during experiments is shown in Fig. 4.2. We modeled two experimental scenarios in the vertical plane: one static and one moving scenario. In Fig. 4.3(a), we show the positions of the static nodes in Vertical Static (VS) scenario. In Fig. 4.3(b), only the destination node is stationary. The other nodes move one floor down and replace each other. The final topology (position) of the nodes is shown in Fig. 4.3(c). We will call this the Vertical Moving (VM) scenario. In fact, it looks like four nodes out of five are moving in VMS, but only one node moves at a time as they shift each other in each floor. We wanted to add more mobility to the testbed, but especially in the vertical plane, we encountered many disconnections when all nodes were moving. A snapshot of nodes during experiments in VS scenario is shown in Fig. 4.2. In Table 4.1, we show the parameters used to perform our experiments.

Table 4.1: Experimental parameters.

Parameters	Values
Number of Nodes	5
MAC	IEEE 802.11b/Channel 2
Transmitted Power	16+/-1 dBm
Flow Type	CBR
Packet Rate	200 pps
Packet Size	256 bytes
Number of Trials	10
Duration	150 sec
Routing Protocol	OLSR, BATMAN

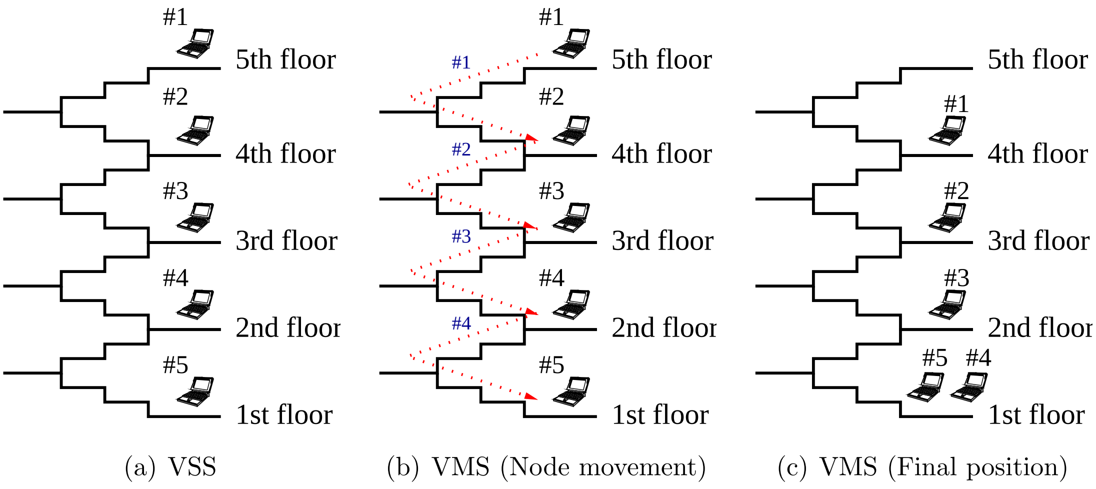
(a) Node ID 1 on 5th floor (b) Node ID 2 on 4th floor (c) Node ID 3 on 3rd floor

(d) Node ID 4 on 2nd floor (e) Node ID 5 on 1st floor

Figure 4.2: Snapshots of nodes for indoor vertical scenarios.

4.2.2 Case 2: Outdoor Bridge

We implemented this case in our academic environment, outside our five-floor academic building (in Fig. 4.4 it is shown as D-Building). There are bridges connecting each floor of D-Building with floors on C-Building. In this case, we conducted experiments using five laptops. We built three experimental scenarios. In Fig. 4.4(a), we show the positions of the static nodes in Outdoor Bridge Static (OBST) sce-



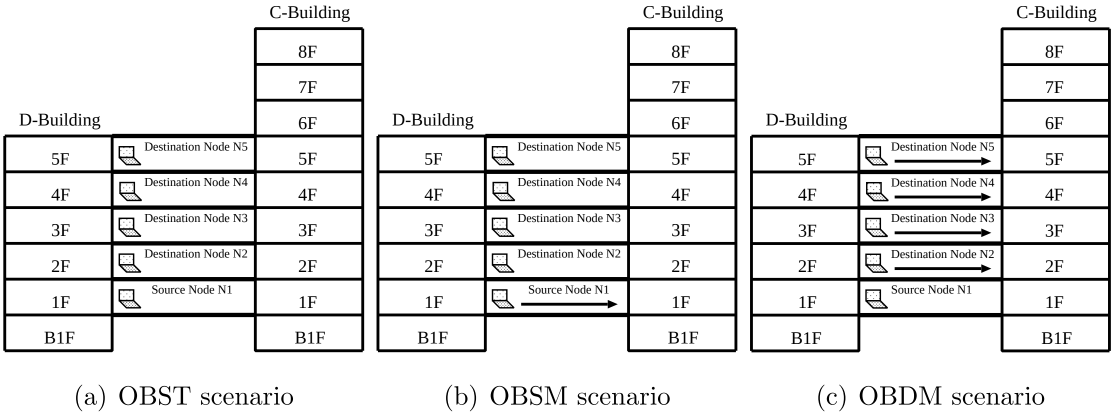
(a) VSS (b) VMS (Node movement) (c) VMS (Final position)

Figure 4.3: Indoor vertical scenarios.

Table 4.2: Experimental parameters.

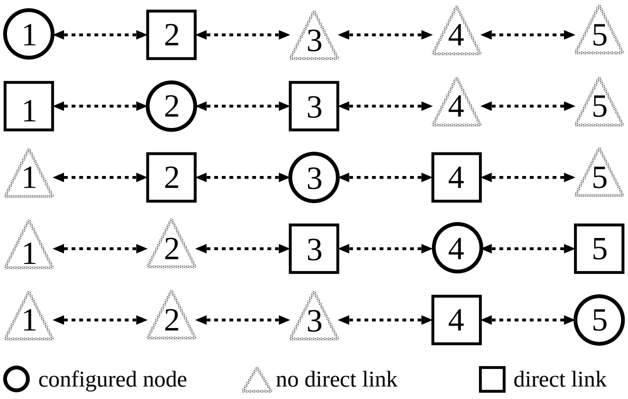
Parameters	Values
Number of Nodes	5
MAC	IEEE 802.11b/Channel 2
Transmitted Power	16+/-1 dBm
Flow Type	CBR
Packet Rate	200 pps
Packet Size	256 bytes
Number of Trials	10
Duration	60 sec
Routing Protocol	BATMAN

nario. In Fig. 4.4(b), the node located in the first floor moves from D-Building to C-Building and back, twice during 60 seconds. We will call this, the Outdoor Bridge Source Moving (OBSM) scenario. In contrary, in Outdoor Bridge Destination Moving (OBDM) scenario, destination nodes are moving by the same pattern as the source node in OBSM scenario (shown in Fig. 4.4(c)). We run the experiments 10 times for every destination. This means during one runtime only one node is moving. Other parameters are shown in Table 4.2



(a) OBST scenario (b) OBSM scenario (c) OBDM scenario

Figure 4.4: Outdoor bridge scenarios.



(a) Node 1

Figure 4.5: Node positioning and MAC filtering for LT.

4.2.3 Case 3: Indoor Multimedia

The experiments are conducted in an indoor environment, inside the fifth floor of our departmental building. We analyze our network for two experimental topologies: Linear Topology (LT) and Mesh Topology (MT). In the earlier, nodes are forced to connect only to specified nodes, through the *iptables* process of Ubuntu, while in the later, nodes can connect with each-other in a mesh fashion. The node position and their settings for the LT Topology are shown in Fig. 4.5

The packet's size is 60 bytes. We sent data with different packet rates, resembling audio data (20-50 pps) and video data (100-800 pps). From now on, we will refer to Audio and Video, respectively. We discuss the effect of multi-hop and data size regarding throughput, delay and packetloss using BATMAN routing protocol. The experimental parameters are shown in Table 4.3.

Table 4.3: Experimental parameters.

Parameters	Values
Number of Nodes	5
MAC	IEEE 802.11b/Channel 2
Transmitted Power	16+/-1 dBm
OS (kernel)	Fedora 14 (2.6.35)
Traffic Generator	D-ITG 2.7.0 Beta2
Packet Rate	$20-50$, $100-800$ pps
Packet Size	60 bytes
Number of Trials	10
Duration	120 sec
Routing Protocol	BATMAN

The data sent to conduct the experiments is transported over UDP. For the Audio data we send the packets with a uniformly distributed rate, varying from 20 to 50 pps. The throughput for this data will vary from $9.6 kbps$ to $24 kbps$, which is almost the same as the throughput for GSM or UMTS audio communications, [48]. For the video data, we use a uniformly distributed packet rate, from 100 to $800 pps$, which corresponds to 48 and 384 $kbps$, respectively.

Chapter 5

Simulators and Simulation Scenarios

Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system [49]. In MANET, simulations are very important to understand the behavior of routing protocols, addressing mechanisms, security algorithms, mobility models, and so on. There are a number of network simulators such as NetSim [50], OPNET [51], Network Simulator version 2/3 (NS2/NS3) [52, 53], which are usually used in the network simulations. In our simulations, we use Network Simulator version 2 (NS2), which is equipped with additional modules and analyzing tools.

5.1 NS2 Simulator System

5.1.1 Introduction

NS2 is a discrete event simulator. It is intended especially on Ad-hoc Networks. It is a unix-based simulator build on different modules and uses TCL scripting language for varying parameters and C++ structured code. Six modules are included in NS2: nodes, links, SimpleLink objects, packets, agents, and applications. There are also three helper modules: timers, random number generators, and error models. NS2 also consists of radio propagation models, traffic generators, topology generators for different mobility models and so on.

5.1.2 Mobility Models

5.1.2.1 Random Waypoint Mobility (RWM) model

RWM model was first proposed by authors in [54] and it is used widely in simulating MANETs. In NS2, this mobility model can be modeled by using the *setdest* tool. In RWM model each node, uncorrelated to each-other, follows the following directions.

1. Selects a random starting position (W_0) in the simulation area ($L\ x\ W$).
2. Selects a random location in the area as the next waypoint (W_i).
3. Starts moving towards the destination W_i, with a randomly chosen speed between V_{min} and V_{max}.
4. After reaching destination W_i, the node pauses for T_p seconds.
5. If T_{max} is reached, end the movement.
6. Repeat steps 2-4.

The movement speed is a key parameter to decide the dynamism of the topology and therefore changes in routes. For low speeds the topology is almost static and for high speeds the topology becomes dynamic and the routes change frequently.

5.1.2.2 2D Random Walk Mobility Model (RW2)

In RW2, each instance moves with a speed and direction chosen at random with the user-provided random variables until either a fixed distance has been walked or until a fixed amount of time. If we hit one of the boundaries (specified by a rectangle), of the model, we rebound on the boundary with a reflexive angle and speed. Node movement is uncorrelated to each-other. This model is often identified as a brownian motion model.

5.2 Simulation Scenarios

5.2.1 Case 1: Static2, OLSR and AODV

We prepared the simulation environment, taking care of the parameters during simulation time, as shown in Table 5.1. The size of the simulation area is $1000m$ x

Table 5.1: Simulation Settings.

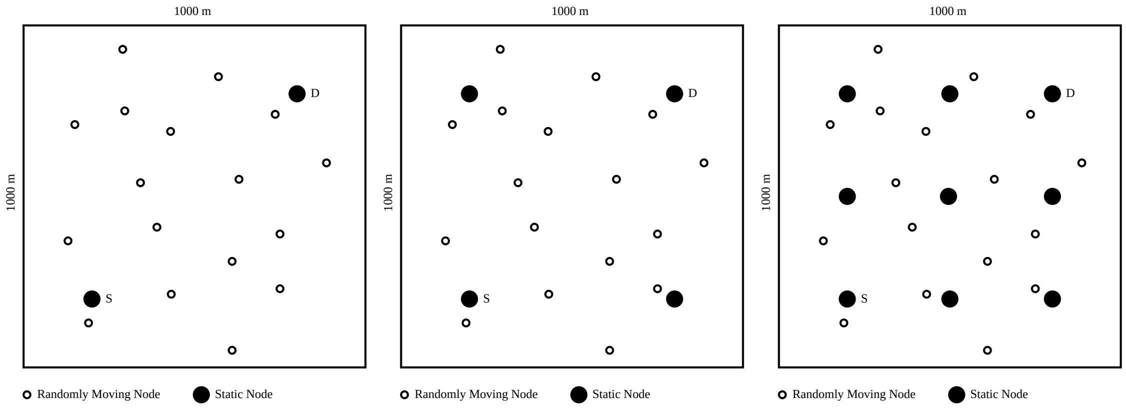
Functions	Values
Area Size	$1000m$ x $1000m$
Number of Nodes	50 or 100
Transmission Range	$250m$
Simulation Time	$300s$
Speed Distribution	$1-5$ or $15-30$ m/s
Pause Time	$2s$
Packet Rate	200 pps
Packet Size	230 bytes
Routing Protocol	OLSR & AODV
OLSR HELLO Interval	$2s$
OLSR TC Interval	$5s$

$1000m$ and we use 50 or 100 nodes distributed randomly in this area. We would like to observe the difference between a sparser network (50 nodes in the area) and a denser network (100 nodes in the area). All nodes move randomly based on RWM model, as explained in the previous subsection. In two cases, nodes move with randomly chosen speeds uniformly distributed in intervals $1-5$ m/s and $15-30$ m/s. In the first case the topology of the network is almost stable and the changes in routes are minimal. While in the second case the topology becomes more dynamic. The pause time is set to a constant 2s. We consider four different topology cases:

- Case A: 50 nodes, which move with speeds 1-5 m/s,
- Case B: 50 nodes, which move with speeds 15-30 m/s,
- Case C: 100 nodes, which move with speeds 1-5 m/s,
- Case D: 100 nodes, which move with speeds 15-30 m/s.

5.2.2 Case 2: Static2, Static4, Static9

In this case, we consider the parameters shown in Table 5.2. All nodes move randomly based on RWM model, with speed uniformly distributed in intervals $1-3$ m/s



(a) Static2 (b) Static4 (c) Static9

Figure 5.1: Node positions.

Table 5.2: Simulation Settings.

Functions	Values
Area Size	$1000m$ x $1000m$
Number of Nodes	40 or 80
Transmission Range	$250m$
Simulation Time	$300s$
Speed Distribution	$1-3$ or $2-8$ m/s
Pause Time	$2s$
Packet Rate	200 pps
Packet Size	230 bytes
Routing Protocol	AODV

and $2-8$ m/s. We chose the speed intervals in order to increase have a little change of the dynamism of routes. We built four different topology cases:

- Case A: 40 nodes, which move with speeds 1-3 m/s,
- Case B: 40 nodes, which move with speeds 2-8 m/s,
- Case C: 80 nodes, which move with speeds 1-3 m/s,
- Case D: 80 nodes, which move with speeds 2-8 m/s.

In Fig. 5.1, we describe the static nodes position for three scenarios. In all scenarios, the source and destination nodes are positioned in $S(200, 200)$ and $D(800, 800)$, respectively. In Static2 (two nodes are static) scenario (Fig. 5.1(a), all other nodes are moving according to RWM model. In Static4 scenario, there are two other nodes in positions $(200, 800)$ and $(800, 200)$, as shown in Fig. 5.1(b). In Fig. 5.1(c) is shown the position of nine static nodes, which create Static9 scenario. We notice that the distance between static nodes is more than $250m$, so they can not create direct links between each-other.

We wanted to compare the performance of three scenarios with the pattern where all nodes were mobile, including source and destination. But, when source and destination nodes are moving, the number of hops that a packet needs to reach the destination is obviously related to the distance between the two nodes. On the other hand, the distance itself is a function, which is related to the randomness of way-point selection for the couple of nodes in discussion. This means that the distance between nodes is also a random function. Thus, the number of hops also changes randomly and the performance of the communication will be mostly affected by the randomness of the RWM model, than by any properties of routing protocols.

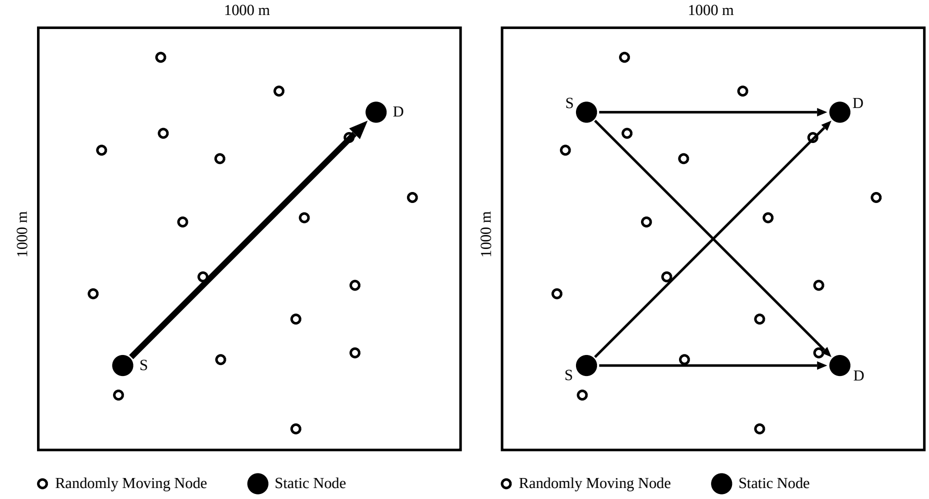
For this reason, we compare the results of three scenarios, where at least source and destination nodes are static and investigate the effect of other static nodes added in the simulation field.

5.2.3 Case 3: RREQ, RREP, RERR, HELLO for AODV

In Fig. 5.2, we describe the static position of nodes for our scenario. We send single-flow data from source and destination nodes, which are positioned in $S(200, 200)$ and $D(800, 800)$, respectively (as shown in Fig. 5.2(a)). All other nodes are moving according to RWM model. We should note that the distance between static nodes is around $850m$ and the packets need at least 4 hops to reach the destination. In Fig. 5.2(b), we show the scenario, when we send 4 flows in the network, using two source nodes and two destination nodes. The parameters of the simulations are shown in Table 5.4.

5.2.4 Case 4: Data Replication in MANET

Data grids deal with a huge amount of data regularly. It is a fundamental challenge to ensure efficient accesses to such widely distributed data sets. Creating replicas to



(a) single (b) multiple

Figure 5.2: Simulation scenarios.

Table 5.3: Simulation Settings.

Functions	Values
Area Size	$1000m$ x $1000m$
Number of Nodes	20, 40, 60 and 80
Transmission Range	$250m$
Simulation Time	$300s$
Speed Distributions (m/s)	$1-5$, $5-10$, $10-20$, $20-30$
Pause Time	$2s$
Packet Rate	200 pps
Packet Size	230 bytes
Routing Protocol	AODV

a suitable node by data replication strategy can increase the system performance. It shortens the data access time and reduces bandwidth consumption.

In this simulation case we propose a realistic fuzzy-based system, which is based on replication of data in some MANET nodes. The replication strategy which uses fuzzy logic, decides the minimal number of replicas that should be created in order to make sure the required performance is satisfied. Selecting a node for the placement of replica is attributed to various factors such as number of requests for a particular file, bandwidth, read/write statistics and location of the resources [55], access cost [56] or data importance [57].

Table 5.4: Simulation Settings for Case 3.

Functions	Values
Area Size	$1000m$ x $1000m$
Number of Nodes	20, 40, 60, 80 and 100
Transmission Range	$250m$
Simulation Time	$300s$
Speed Distributions (m/s)	$1-5$, $5-10$, $10-20$, $20-30$
Pause Time	$2s$
Packet Rate	200 pps
Packet Size	230 bytes
Routing Protocol	AODV

In the following, we present the parameters which are important to determine our solutions to data replication in MANETs. It should be noted that creating as many replicas as possible might not be a good solution in MANETs.

5.2.4.1 Simulation Parameters

Local Node Density: In a MANET, a node can have different number of neighbors at a given time. The throughput supplied to each node in an ad-hoc network approaches to zero asymptotically as the density increases [58]. Network density is a key parameter to planning network capacities.

Most of routing algorithms calculate one-hop or two-hop neighbors in order to make their decisions. The authors of [59] proposed to calculate node density using beacons. In our system Local Node Density (LND) is a parameter, which affects the number of replicas that should be created in a given area. Let us consider the case when only one node has the replica in a given area. If LND of this node is low (i.e. 2 neighbor nodes), the replica it is holding will serve only to those two nodes, so we need to increase the number of replicas if we want to make the data efficiently accessible in all the network.

Maximum Data Accessibility and Number of Hops: As a result of data replication all nodes in a MANET can access a given data, in probably many routes, each with different number of hops and different link quality. According to the routing protocol used in the network, a node can choose different routes, with different number of hops to get the data. Here, we want to introduce a parameter to measure the maximum number of hops that a node will need to access the data in the network. We will call it Maximum Data Accessibility Hop Number (MDAHN).

Less replicas are enough to guarantee big MDAHN, which means less traffic around the network. On the other hand, we want to make MDAHN smaller in order to guarantee a bounded data retrieval time. There is a problem with this in MANETs, which is inevitable because of mobility of nodes. When the topology changes dynamically, in order to keep MDAHN, creating and deleting replicas creates a traffic which quantity is probably comparable to the traffic caused by routing protocol. We will leave it as future work to investigate quantitative results.

Guaranteed Bounded Retrieval Time: To retrieve a data from a distant node, a certain time is needed. The number of hops, actual network conditions and mobility affect data retrieval time in MANET. This retrieval time has limitations in some real-time applications, where if data retrieval time is high, the system can degrade or even worse be useless. How to guarantee a Bounded Retrieval Time (BRT) in a MANET is a difficult problem. The number of replicas will increase if we need a low data retrieval time. But, if the retrieval time is not an issue, the number of replicas can be smaller.

Minimal Number of Replicas Current works on data replications in distributed systems focus on infrastructure for replication mechanism for creating or deleting replicas. One of the challenges in data replication is determining the Minimal Number of Replicas (MNR) with guaranteed QoS, as well as their optimal location in the network [60].

The number of replicas for each data in the network is determined by different factors, included but not limited to those mentioned above. In our work, we concentrate on determining a MNR for each data, in order to guarantee network performance parameters.

5.2.4.2 Proposed Fuzzy-based Data Replication System

The structure of the proposed system is shown in Fig. 5.3. We explain in details the design of Fuzzy-based Data Replication system for MANET (FDRM) in following.

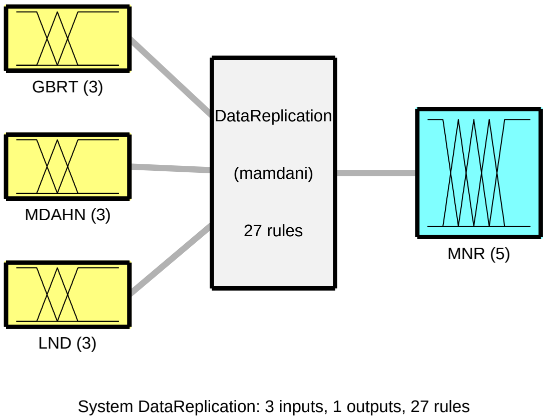


Figure 5.3: Input and Output of the FDRM System.

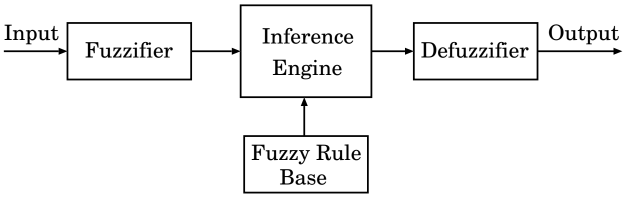


Figure 5.4: FLC structure.

The Fuzzy Logic Controller (FLC) is the main part of FDRM and its basic elements are shown in Fig. 5.4. They are the fuzzifier, inference engine, Fuzzy Rule Base (FRB) and defuzzifier.

As shown in Fig. 5.5, as membership functions we use triangular and trapezoidal membership functions because they are suitable for real-time operation [61]. We use three input parameters,

- Guaranteed Bounded Retrieval Time (GBRT);
- Maximum Data Accessibility Hop Number (MDAHN);
- Local Node Density (LND).

The fuzzy membership functions for them are shown in Fig. 5.6 and their term sets are shown in Table 5.5.

The term sets for each input linguistic parameter are defined respectively as:

$$\begin{aligned} T(GBRT) &= \{Fast(Fa), Medium(Me), Slow(Sl)\}; \\ T(MDAHN) &= \{Low(Lo), Medium(Me), High(Hi)\}; \end{aligned}$$

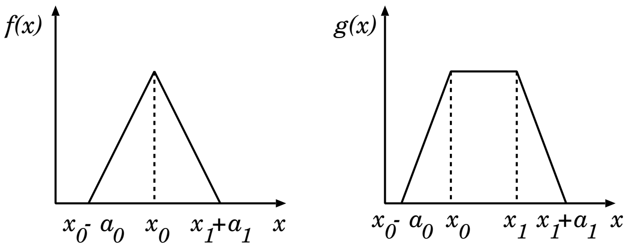


Figure 5.5: Triangular and trapezoidal membership functions.

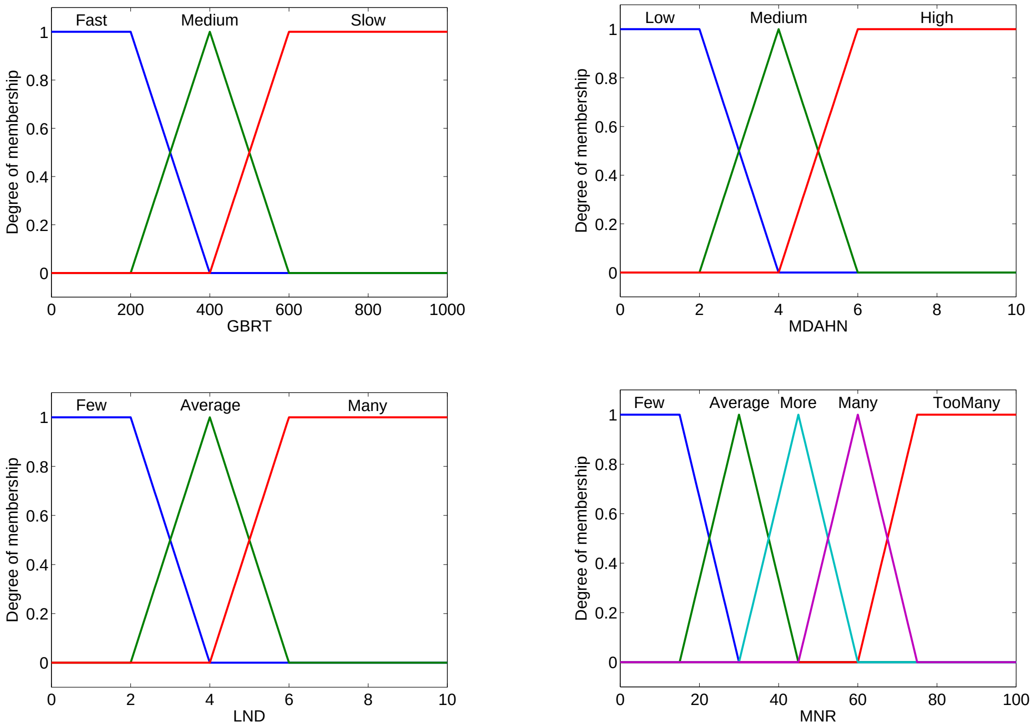


Figure 5.6: Membership functions.

$$T(LND) \quad = \quad \{Few(Fe), Average(Av), Many(Ma)\}.$$

The membership functions for input parameters of FLC are defined as:

$$\begin{aligned}
\mu_{Fa}(GBRT) &= g(GBRT; Fa_0, Fa_1, Fa_{w0}, Fa_{w1}); \\
\mu_{Me}(GBRT) &= g(GBRT; Me_0, Me_{w0}, Me_{w1}); \\
\mu_{Sl}(GBRT) &= g(GBRT; Sl_0, Sl_1, Sl_{w0}, Sl_{w1}); \\
\mu_{Lo}(MDAHN) &= g(MDAHN; Lo_0, Lo_1, Lo_{w0}, Lo_{w1}); \\
\mu_{Me}(MDAHN) &= f(MDAHN; Me_0, Me_{w0}, Me_{w1}); \\
\mu_{Hi}(MDAHN) &= g(MDAHN; Hi_0, Hi_1, Hi_{w0}, Hi_{w1}); \\
\mu_{Fe}(LND) &= g(LND; Fe_0, Fe_1, Fe_{w0}, Fe_{w1});
\end{aligned}$$

Table 5.5: Parameters and their term sets.

Parameters	Term Sets
Guaranteed Bounded Retrieval Time (GBRT)	Fast, Medium, Slow
Maximum Data Accessibility Hop Number (MDAHN)	Low, Medium, High
Local Node Density (LND)	Few, Average, Many
Minimal Number of Replicas (MNR)	Few, Average, More, Many, TooMany

$$\begin{aligned}
\mu_{Av}(LND) &= f(LND; Av_0, Av_{w0}, Av_{w1});\\
\mu_{Ma}(LND) &= g(LND; Ma_0, Ma_1, Ma_{w0}, Ma_{w1});
\end{aligned}$$

The small letters *w0* and *w1* mean left width and right width, respectively.

The output linguistic parameter is the Minimal Number of Replicas (MNR). We define the term set of MNR as: $\{$*Few* (Fe), *Average* (Av), *More* (Mo), *Many* (Ma), *Too Many* (Tm)$\}$.

The membership functions for the output parameter *MNR* are defined as:

$$\begin{aligned}
\mu_{Fe}(MNR) &= g(MNR; Fe_0, Fe_1, Fe_{w0}, Fe_{w1});\\
\mu_{Av}(MNR) &= f(MNR; Av_0, Av_{w0}, Av_{w1});\\
\mu_{Mo}(MNR) &= f(MNR; Mo_0, Mo_{w0}, Mo_{w1});\\
\mu_{Ma}(MNR) &= f(MNR; Ma_0, Ma_{w0}, Ma_{w1});\\
\mu_{Tm}(MNR) &= f(MNR; Tm_0, Tm_1, Tm_{w0}, Tm_{w1}).
\end{aligned}$$

The FRB (shown in Table 5.6) forms a fuzzy set of dimensions $|T(GBRT)| \times |T(MDAHN)| \times |T(LND)|$, where $|T(x)|$ is the number of terms on $T(x)$. The FRB has 27 rules. The control rules have the form: IF "conditions" THEN "control action".

Table 5.6: Fuzzy Rule Base.

Rule	GBRT	MDAHN	LND	MNR
1	Fa	Lo	Fe	VF
2	Fa	Lo	Av	VF
3	Fa	Lo	Ma	VF
4	Fa	Me	Fe	LS
5	Fa	Me	Av	MD
6	Fa	Me	Ma	LF
7	Fa	Hi	Fe	VS
8	Fa	Hi	Av	VS
9	Fa	Hi	Ma	VS
10	Me	Lo	Fe	VF
11	Me	Lo	Av	VF
12	Me	Lo	Ma	VF
13	Me	Me	Fe	S
14	Me	Me	Av	LS
15	Me	Me	Ma	MD
16	Me	Hi	Fe	VS
17	Me	Hi	Av	VS
18	Me	Hi	Ma	VS
19	Sl	Lo	Fe	VF
20	Sl	Lo	Av	VF
21	Sl	Lo	Ma	VF
22	Sl	Me	Fe	VS
23	Sl	Me	Av	S
24	Sl	Me	Ma	LS
25	Sl	Hi	Fe	VS
26	Sl	Hi	Av	VS
27	Sl	Hi	Ma	VS

Chapter 6

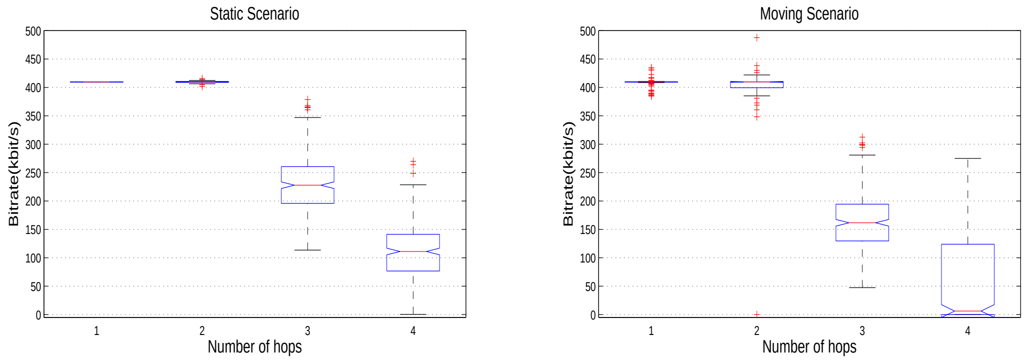
Experimental Results

IN this section we will present the result of our experiments. we implemented three different cases in different environments and topologies. We show the results in statistical display showing the median values of the entire communication. We also show time-domain plots and average data in order to have a general understanding of the performance. We used throughput, delay and packetloss as metrics for performance assessment of OLSR, AODV and BATMAN routing protocols.

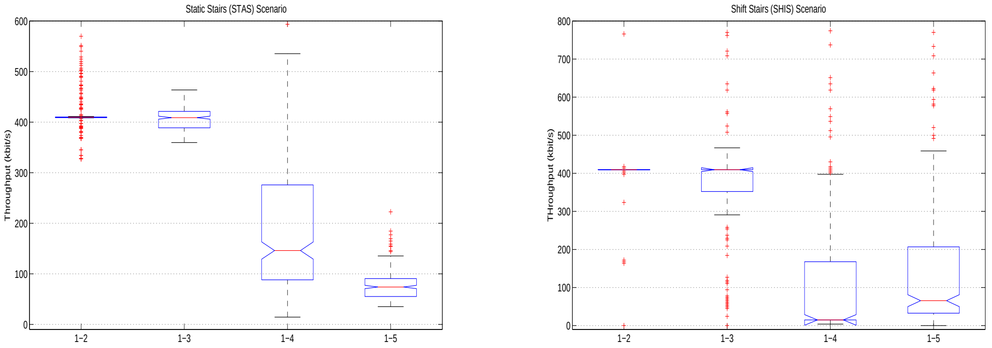
6.1 Case1: Indoor Stairs

We show the throughput results in Fig. 6.1 and Table 6.1. In Fig. 6.1(a) and Fig. 6.1(c), we show the throughput results for STAS scenario. For communication flow from node 1 to node 2 and node 3, the throughput has only a few oscillations and its average value is very close to DTR (409.6 kbps) for both protocols. When the data flows from node 1 to node 4 or node 5 in STAS scenario the oscillations are increased noticeably. The average throughput value for the communication from node 1 to node 4 is almost 50 % lower than DTR and when data flows from node 1 to node 5 throughput is about 100 kbps (25% of DTR).

Also in SHIS scenario, for three-hop and four-hop communications we notice oscillations. When we use BATMAN, the two-hop communication presents more oscillations than in the case of OLSR. The average values for OLSR and BATMAN decrease by 5% and 15% respectively, when the communications occurs in two hops. For the average values of each flow see Table 6.1.



(a) STAS scenario (OLSR) (b) SHIS scenario (OLSR)



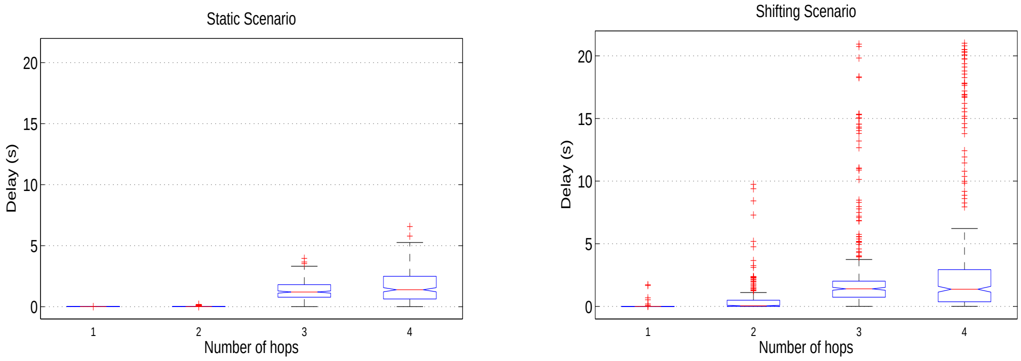
(c) STAS scenario (BATMAN) (d) SHIS scenario (BATMAN)

Figure 6.1: Throughput results.

Table 6.1: Average throughput (kbit/s).

Flow	Floor	STAS Scenario		SHIS Scenario	
		OLSR	BATMAN	OLSR	BATMAN
1→2	4th	409.60	409.60	409.59	409.25
1→3	3rd	409.53	407.23	391.77	345.12
1→4	2nd	232.42	184.50	166.29	132.53
1→5	1st	112.79	76.78	63.43	146.54

In SHIS scenario, when transmitting from node 1 to node 5, we notice the throughput for BATMAN increases in comparison to 1→4 transmission. As shown in Fig. 4.3(c), node 5 is in static state during experimental time for SHIS scenario. Also, at the final position of SHIS scenario, nodes are closer to each other and the links have better quality, which results in better performance.



(a) STAS scenario (OLSR)

(b) SHIS scenario (OLSR)

Figure 6.2: Delay results.

Table 6.2: Average delay (s).

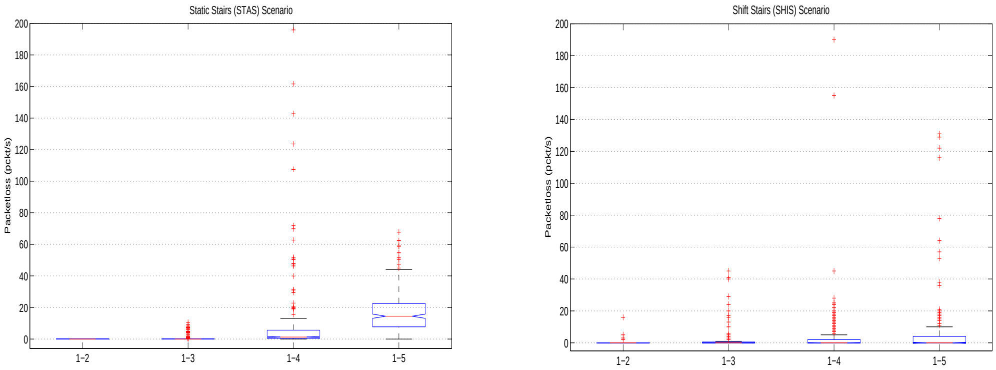
Flow	Floor	STAS Scenario		SHIS Scenario	
		OLSR	BATMAN	OLSR	BATMAN
1→2	4th	0.0045	0.0198	0.0209	0.0241
1→3	3rd	0.0210	0.0885	0.4754	0.7207
1→4	2nd	1.3185	2.6800	2.6742	3.6724
1→5	1st	1.6403	4.0517	3.5424	4.4339

Table 6.3: Average Packetloss (pps).

Flow	Floor	STAS	SHIS
1→2	4th	0	0.0867
1→3	3rd	0.4703	10.7967
1→4	2nd	37.5783	57.0733
1→5	1st	49.7510	30.8267

In STAS scenario, the delay values for both protocols increase constantly when the number of hops increases. When we use BATMAN as a routing protocol, for the 1→5 flow, we notice great oscillations. However the average value in this case is 4.05s (see Table 6.2).

For SHIS scenario, the oscillations start to become noticeable since the two-hop communication, for both OLSR and BATMAN. The average values become more



(a) Packet loss for STAS scenario

(b) Packet loss for SHIS scenario

Figure 6.3: Packetloss results for STAS and SHIS scenarios.

than 2.5s when the data flows are transmitted through three or four hops. However, OLSR shows a better performance than BATMAN regarding the delay metrics.

When the destination node is node 5 there is an improvement in performance for both OLSR and BATMAN protocols. When the destination node is static (1→5 flow), the throughput is greater than when destination node is moving (1→4 flow), even though the communication needs more hops.

In general, OLSR shows a better performance than BATMAN. However, BATMAN has an extra feature. BATMAN does not drop packets directly, when routes are unstable, but keeps them in a buffer. For SHIS scenario, when transmitting from node 1 to node 5, the throughput of BATMAN is increased. However, the buffering feature also increases the delay.

6.2 Case2: Outdoor Bridge

We show the throughput results in Fig. 6.4 while in Fig. 6.5 we show the results for the packetloss. In Fig. 6.4(a), 6.4(b) and Fig. 6.4(c), the boxplots of throughput results are shown for OBST, OBSM and OBDM respectively. In the following, we will discuss the results of our experiments.

For one-hop communications there are not many oscillations for all three scenarios. During the experiments, the movement of the nodes, did not bring any disconnection in the first hop of the communication. This can be seen also in Figs.

6.5(a)-6.5(c), regarding the packetloss. The throughput is almost the same as DTR and packetloss is almost 0.

When the packets use 2 or more hops to reach the destination (flow 1 → 3, 1 → 4 and 1 → 5), there are oscillations for both throughput and packetloss. This is obvious, because for more number of hops, more packets will be processed (sent and received). This increases the probability of packets loss, thus throughput is decreased.

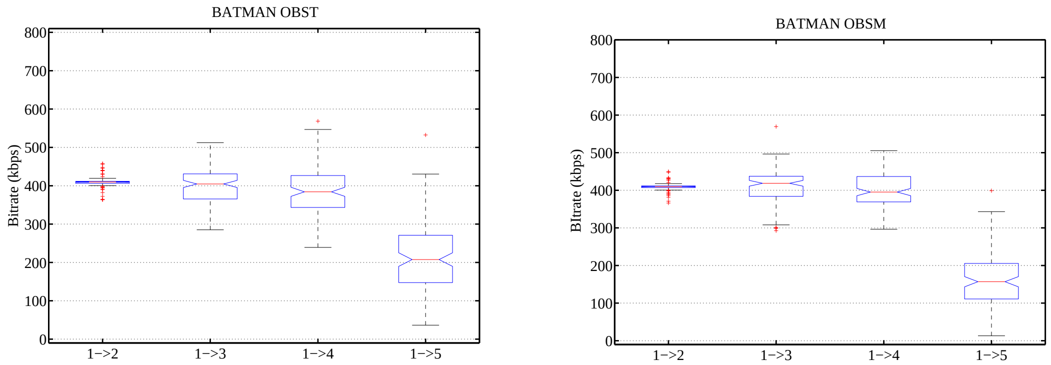
However, for 1 → 5 flow, the throughput decreases to less than half of the sent DTR and the packetloss increases to noticeable values. When the data flows from node 1 to node 5, the packets go through 3 or 4 hops to reach the destination. As also mentioned in other works [62,63], the communication for three or more hops in a MANET testbed becomes difficult.

Another reason that affects the performance of the network is the material of the environment. The bridges, which connect the two buildings, are constructed by metal, which absorbs the electromagnetic waves. We would like to have a more detailed investigation on that on our future work.

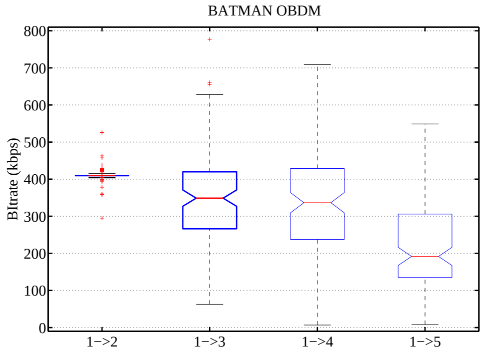
6.3 Case3: Multimedia Transmissions

We show throughput results during 120 seconds of data transmission, in Fig. 6.6. In Tables. 6.4, 6.5 and 6.6, are shown the minimum, maximum and average values of throughput, delay and packetloss, respectively. In Figs. 6.6(a) and 6.6(b), is shown the throughput of audio flow transmission for both LT and MT. We notice that the performance is almost the same for both topologies. The throughput has a few oscillations, but it stays at almost the same levels for all communications (1 → 2, 1 → 3, 1 → 4 and 1 → 5). If we look at Fig. 6.6(c), where we have a video transmission with LT, the performance for 1 → 2 flow is the best, and the performance decrease as the number of hops increases up to 4 hops in 1 → 5 flow. However 2-hop and 3-hop communications have similar performance. On the other hand, for MT in Fig. 6.6(d), we can see that the performance for 1 → 2, 1 → 3 and 1 → 4 flows are almost similar, while in case of 1 → 5 flow, the values of throughput fall to around $20kbps$.

Comparing the results of Fig. 6.6 and Table 6.4, we can see clearly that for audio (small data rates) there is no difference between LT and MT, but for larger data



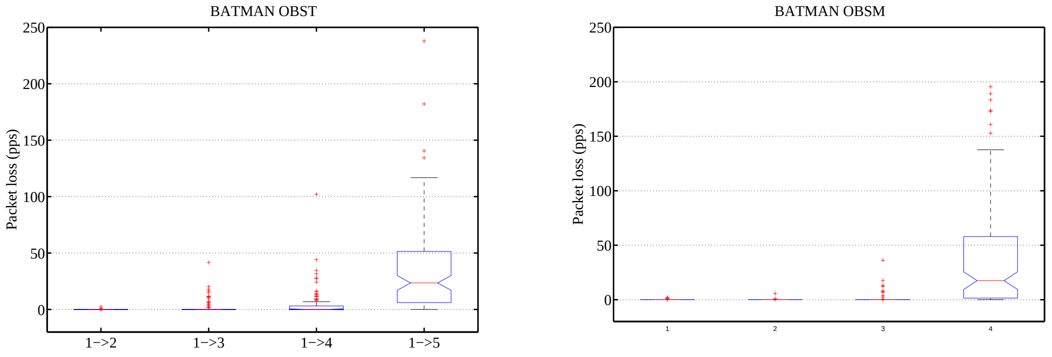
(a) bitrate (OBST)
(b) bitrate (OBSM)



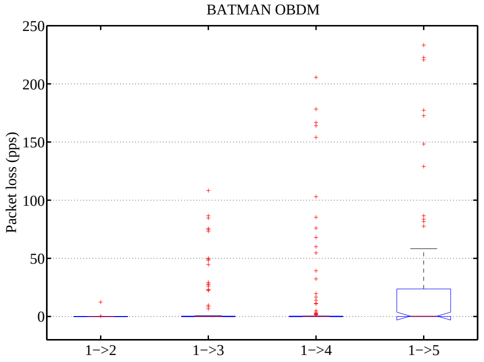
(c) bitrate (OBDM)

Figure 6.4: Bitrate experimental results.

rates, in MT case the average throughput decreases and the oscillations increase. In LT scheme, one node can receive OGMs only from its neighbors, so the number of received OGMs from other nodes is zero. This means that the route from node 1 to other nodes, are always known and unchangeable. However there is an unchangeable 4-hop transmission from node 1 to node 5. In the MT scheme, lets say, node 1 wants to transmit to node 5 with the high rate video transmission of 48-384 pps. First, the best 1-hop neighbor is node 2 and it starts to send packets to node 2. Meanwhile, the 1 → 2 link is busy and node 1 receives from node 3 some OGMs broadcast by node 5, so that node 3 becomes the best 1-hop neighbor. Then, while the 1 → 3 link is busy, it will happen the opposite. This instability in routes brings oscillations and decrease in throughput. The packetloss, shown in Table 6.6, is closely related to throughput and it has a similar behavior. We can see that for audio data the packetloss is very small so the performance is very good.



(a) packetloss (OBST) (b) packetloss (OBSM)



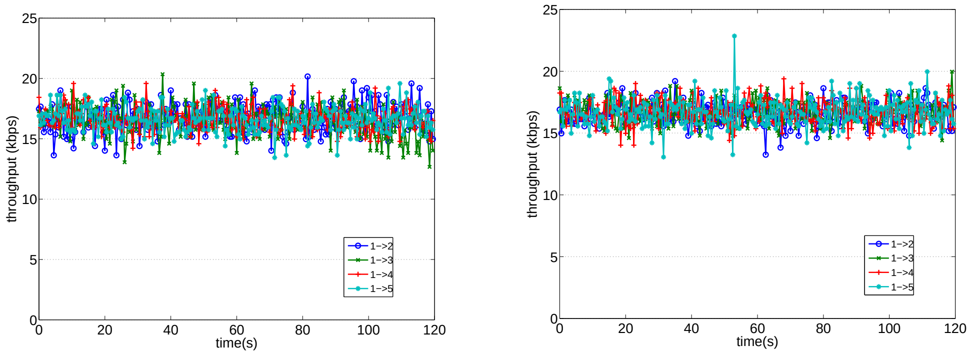
(c) packetloss (OBDM)

Figure 6.5: Packetloss experimental results.

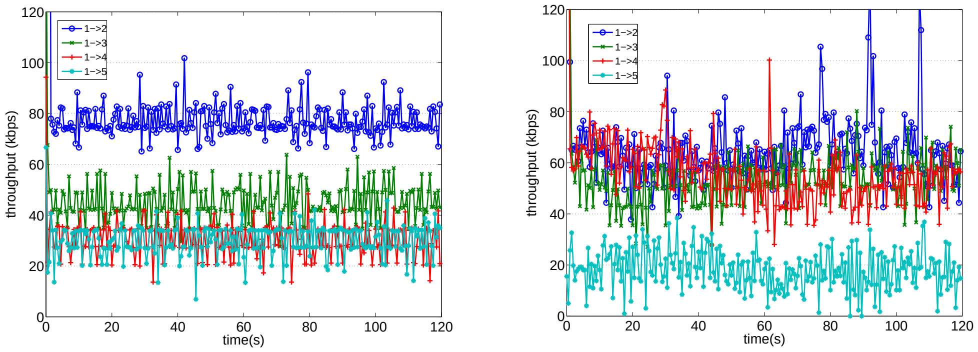
Table 6.4: Throughput results (kbit/s).

Flow	Audio (9.6-24 kbps)						Video (48-384 kbps)					
	LT			MT			LT			MT		
	min	max	av	min	max	av	min	max	av	min	max	av
1→2	13.63	20.16	16.73	13.25	19.20	16.57	65.09	360.19	80.12	38.82	220.99	65.74
1→3	12.67	20.35	16.46	14.40	19.97	16.69	27.65	161.86	45.41	27.07	253.06	55.04
1→4	14.21	19.58	16.64	14.02	19.39	16.69	13.63	94.27	30.74	27.84	226.18	56.87
1→5	13.44	19.58	16.58	13.06	22.85	16.67	6.91	66.24	30.08	0.96	38.40	18.28

Regarding delay, we show the results in Table 6.5. The average delay for audio transmissions, for LT and MT is under 20 ms and 10 ms, respectively. For video transmissions, delay reaches values up to 9 seconds, in case of 1 → 5 flow for LT. The number of hops for LT is 4 hops. Packets traveling through 4 hops, takes more time to reach the destination.



(a) Audio data, LT (b) Audio data, MT



(c) Video data, LT (d) Video data, MT

Figure 6.6: Throughput results.

Table 6.5: Delay results (s).

Flow	Audio (9.6-24 kbps)						Video (48-384 kbps)					
	LT			MT			LT			MT		
	min	max	av	min	max	av	min	max	av	min	max	av
1→2	0.006	0.075	0.012	0.002	0.045	0.004	0.081	0.927	0.735	0.150	1.640	1.285
1→3	0.007	0.063	0.015	0.002	0.066	0.005	0.181	3.978	3.581	0.121	1.801	1.137
1→4	0.005	0.092	0.016	0.002	0.086	0.004	0.230	6.742	5.161	0.155	2.581	1.497
1→5	0.007	0.117	0.018	0.002	0.088	0.007	0.236	12.955	9.461	0.221	14.154	6.010

Table 6.6: Packetloss results (pps).

Flow	Audio (9.6-24 kbps)						Video (48-384 kbps)					
	LT			MT			LT			MT		
	min	max	av	min	max	av	min	max	av	min	max	av
1→2	0	0.2	0.003	0	0.2	0.004	0	372.6	128.8	0	6042	237.5
1→3	0	1.2	0.026	0	0.4	0.005	0	364.0	138.8	0	7021	256.8
1→4	0	1.4	0.043	0	0.2	0.003	0	326.8	145.8	0	7408	283.1
1→5	0	2.0	0.032	0	2.6	0.025	0	395.2	171.7	0	8620	405.2

Chapter 7

Simulation Results

We conducted simulations for different scenarios in our NS2-based simulation system We consider four simulation cases for different applications of MANETs. We investigate the effect of static components in the performance of MANET routing protocols. A data replication simulation framework is also evaluated in the fourth case.

7.1 Case 1: Static Source and Destination for OLSR and AODV

In Fig. 7.1, we show the distance between source and destination nodes. It is also shown the number of hops that packets need to go from source to destination. All nodes are moving according to RWM model. We will refer to this as All Move (ALMOV) scenario. We can see that the number of hops is directly related to the distance between nodes.

The average values of throughput are shown in Table 7.1 and Table 7.2. In ALMOV scenario, the distance changes randomly in different topologies. The number of hops also changes with the change of distance. In SDSTA scenario the distance is fixed to 848.53 meters as shown in Table 7.1.

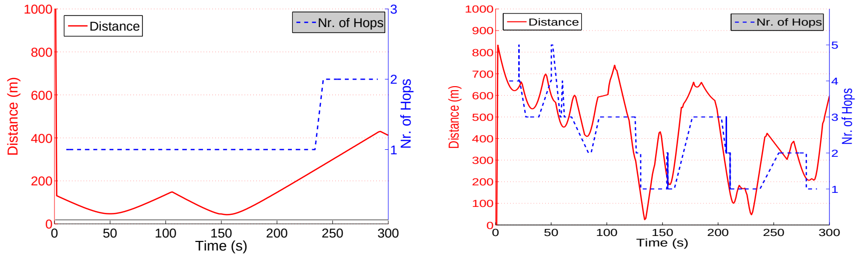
We conducted simulations for 4 topologies considering OLSR and AODV protocol. The OLSR patch can be found in [64]. For all cases, we show distance versus number of hops for ALMOV and SDSTA scenarios, in Fig. 7.1 and Fig. 7.2, respectively. The data sent from source node to destination node is CBR type transported

Table 7.1: Average throughput values for ALMOV Scenario.

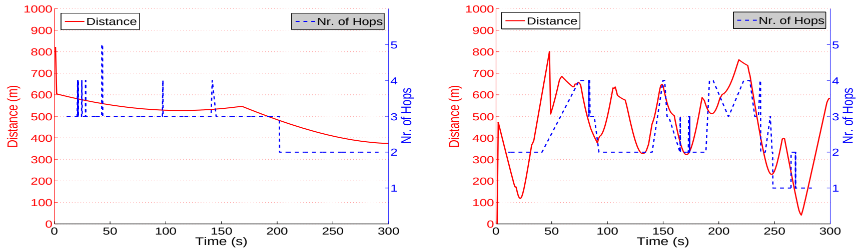
Speed	1-5 m/s		15-30 m/s	
Nr. of nodes	50	100	50	100
Case	A	B	C	D
Distance (m)	160.42	500.27	436.6	457.16
Throughput OLSR (kbps)	303.99	100.91	98.08	34.45
Throughput AODV (kbps)	329.81	145.87	149.69	150.92

Table 7.2: Average values for SDSTA Scenario.

Speed	1-5 m/s		15-30 m/s	
Nr. of nodes	50	100	50	100
Case	A	B	C	D
Distance (m)	848.53	848.53	848.53	848.53
Throughput OLSR (kbps)	35.84	34.45	5.84	5.28
Throughput AODV (kbps)	54.21	59.85	50.87	44.14



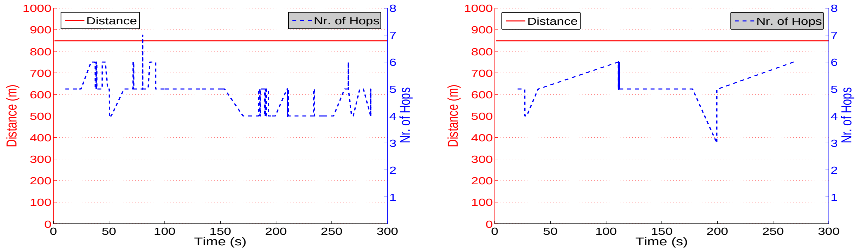
(a) 50N, 1-5 m/s (b) 50N, 15-30 m/s



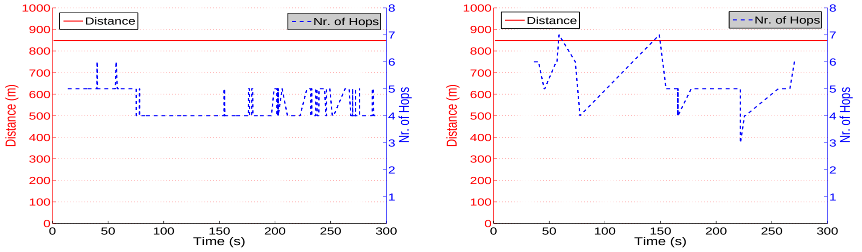
(c) 100N, 1-5 m/s (d) 100N, 15-30 m/s

Figure 7.1: Distance vs. Nr. of Hops (ALMOV).

over UDP. The CBR is 200 pps and the packet size is 230 bytes, thus the Data Transmission Rate (DTR) is $200pps \times 230bytes/packet \times 8bit/bytes = 368000bps = 368kbps$.



(a) 50N, 1-5 m/s (b) 50N, 15-30 m/s



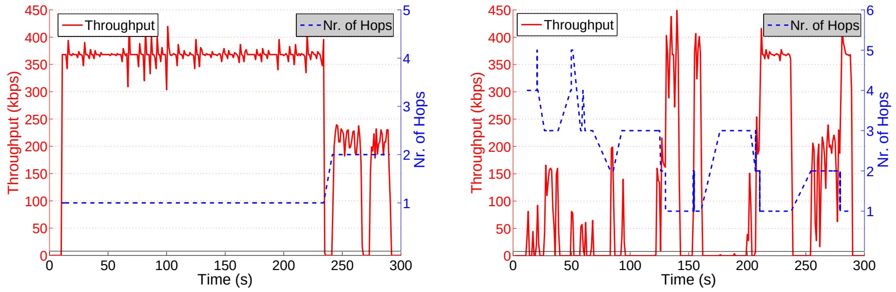
(c) 100N, 1-5 m/s (d) 100N, 15-30 m/s

Figure 7.2: Distance vs. Nr. of Hops (SDSTA).

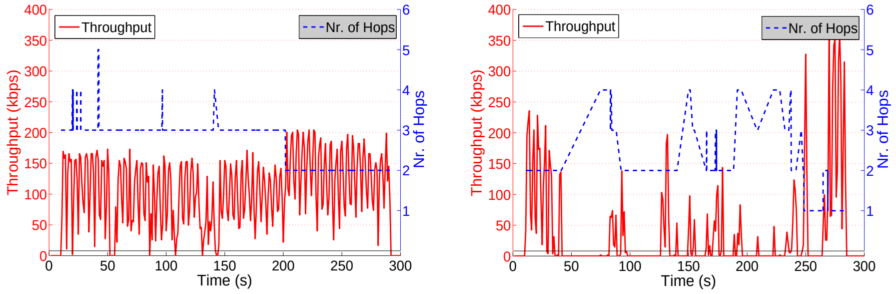
Taking into consideration also the communication distance between nodes (250m), the packets can not be delivered in less than 4 hops. However, in Fig. 7.2, we see oscillations in the number of hops, which is related to the random movement of the intermediate nodes. OLSR's MPR selection procedure chooses a different MPR set when the topology is dynamic. Also AODV's "route request" and "route repair" procedures cause these oscillations, which are a common phenomenon in MANET.

It is obvious from Fig. 7.1 that, when speed of movement is higher (B and D cases), there are more oscillations in the number of hops compared with cases A and C, where the speed is lower. This is more clearly shown in Fig. 7.2, where even the distance between source and destination is the same, the number of hops is different.

For OLSR, throughput measured in kilobits per second (kbps) versus number of hops is shown in Figs. 7.3 and 7.4 for ALMOV and SDSTA scenarios, respectively. For ALMOV scenario, in case A (Fig. 7.3(a)), the source and destination are very near, so the throughput is high, except for the last 50 seconds when the communications occurs in 2 hops. The throughput is inverse proportional with the number of hops. Thus, the throughput is decreased when the number of hops is increased as shown in Table 7.1 and Table 7.2. When the number of hops increases, we can see that there are some disconnections in all cases (see Fig. 7.3). The performance of

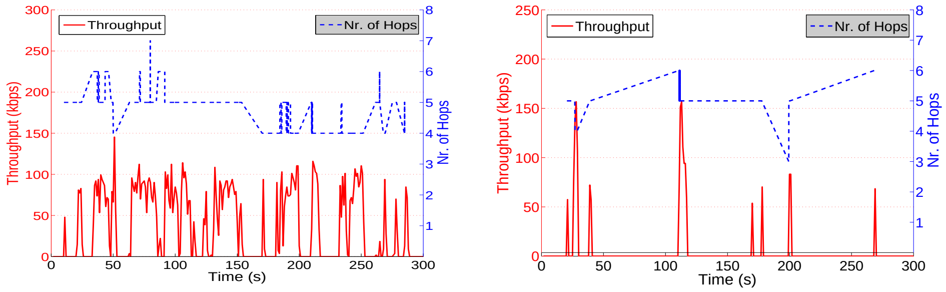


(a) 50N, 1-5 m/s (b) 50N, 15-30 m/s

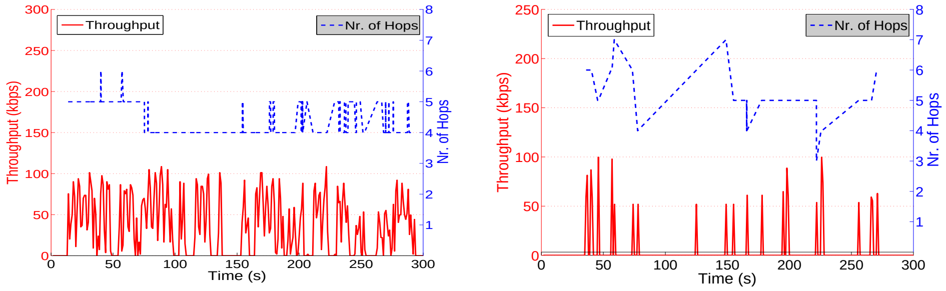


(c) 100N, 1-5 m/s (d) 100N, 15-30 m/s

Figure 7.3: Throughput vs. Nr. of Hops OLSR (ALMOV).

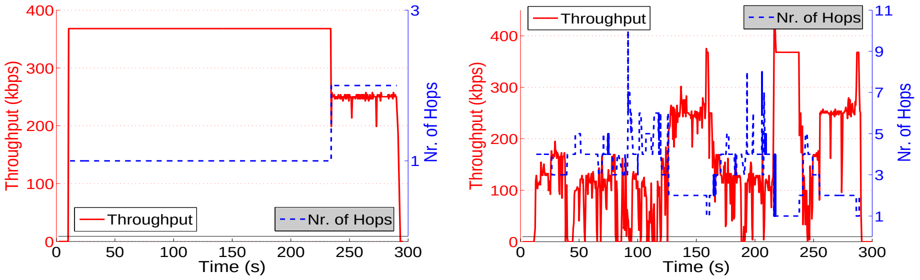


(a) 50N, 1-5 m/s (b) 50N, 15-30 m/s

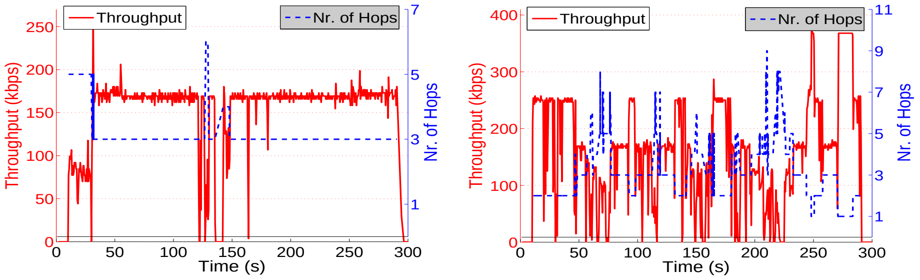


(c) 100N, 1-5 m/s (d) 100N, 15-30 m/s

Figure 7.4: Throughput vs. Nr. of Hops OLSR (SDSTA).

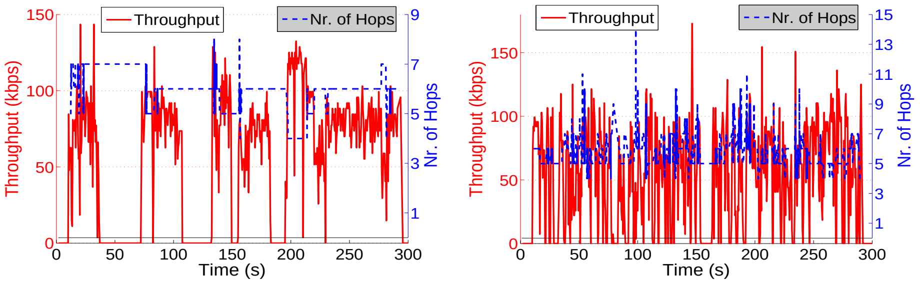


(a) 50N, 1-5 m/s (b) 50N, 15-30 m/s

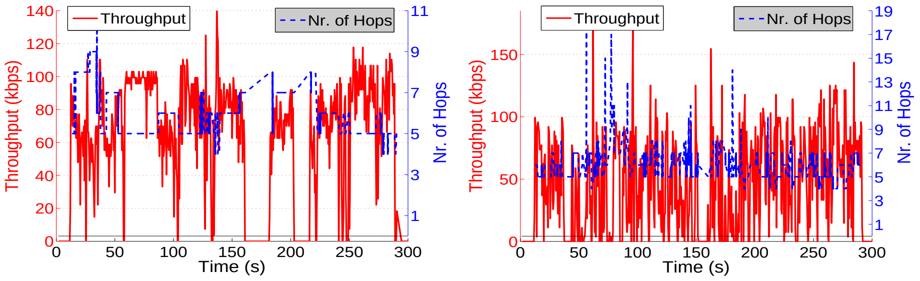


(c) 100N, 1-5 m/s (d) 100N, 15-30 m/s

Figure 7.5: Throughput vs. Nr. of Hops AODV (ALMOV).



(a) 50N, 1-5 m/s (b) 50N, 15-30 m/s



(c) 100N, 1-5 m/s (d) 100N, 15-30 m/s

Figure 7.6: Throughput vs. Nr. of Hops AODV (SDSTA).

throughput decreases in cases B and D, where moving speed is higher. This is also shown in Table 7.2, where the communication distance is the same for all cases.

There are more disconnections in SDSTA scenario, as shown in Fig. 7.4, especially when the speed of movement is higher (in cases B and D), see Fig. 7.4(b) and Fig. 7.4(d). The movement of nodes, brings dynamism to the network topology and there are rapid changes in OLSR nodes' routing tables. The interval of multi-casting `HELLO` messages and `TC` messages in the network is set as default to be 2 seconds and 5 seconds, respectively. So, the topology information is not updated on time to keep 4 or 5-hop routes. As we can see in Fig. 7.4(a) and Fig. 7.4(c), when moving speed is lower, the disconnections are minimized and throughput is higher.

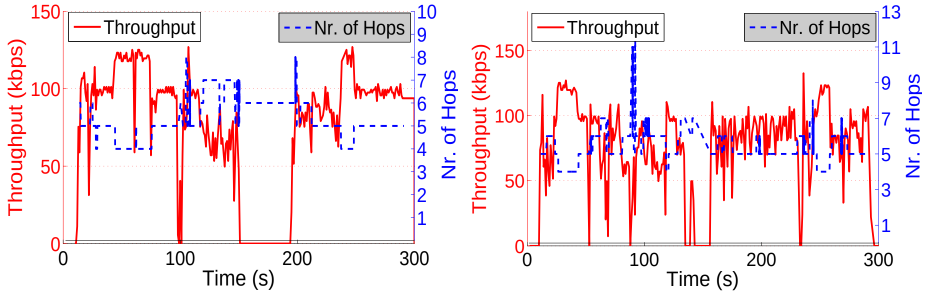
For AODV, throughput measured in kilobits per second (kbps) versus number of hops is shown in Fig. 7.3 and Fig. 7.4 for ALMOV and SDSTA scenarios, respectively. For ALMOV scenario, in case A (Fig. 7.5(a)), both source and destination happens to be very near, so the throughput is in its higher values, except for the last 50 seconds when the communications occurs in 2 hops. Throughput is inversely proportional to the number of hops. The throughput is decreased when the number of hops is increased as shown in Table 7.1 and Table 7.2. The oscillations increase further in SDSTA scenario, where the average number of hops is over 5.5. IN general the performance of AODV is better than that of OLSR.

7.2 Case 2: Static2, Static4, Static9

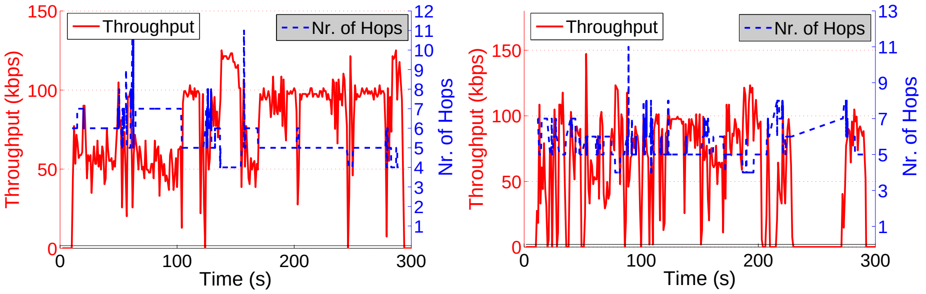
For each scenario, we conducted simulations for 4 cases. We use UDP protocol to transport the data from source node to destination node. The packet rate of Constant Bit Rate (CBR) flow is 200 pps with each packet size of 230 bytes. So, the CBR is $200pps \times 230bytes/packet \times 8bit/bytes = 368000bps = 368kbps$.

The distance from source to destination is fixed to 848.53 meters. Taking in consideration also the communication distance between nodes (250m), the packets can not be delivered in less than 4 hops. However, we notice oscillations in number of hops, which is the result of the random movement of intermediate nodes. We think that the "route request" and "route repair" procedures of AODV cause these oscillations, which are a common phenomenon in MANET.

In Figs. 7.7, 7.8 and 7.9, we show time domain results for three scenarios, respectively. During 300 seconds of simulation, we show the throughput (kbps) on the left y-axis and number of hops in the right y-axis.

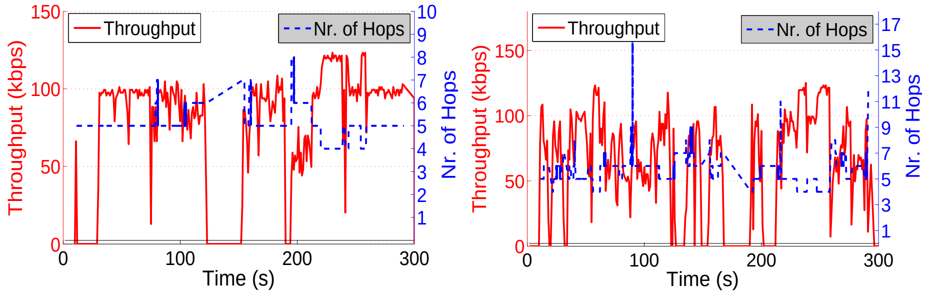


(a) 40N, 1-3 m/s (A) (b) 40N, 2-8 m/s (B)

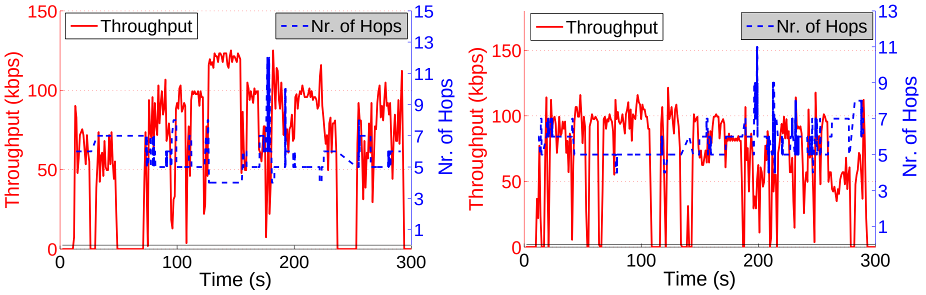


(c) 80N, 1-3 m/s (C) (d) 80N, 2-8 m/s (D)

Figure 7.7: Throughput vs. Number of Hops (Static2)

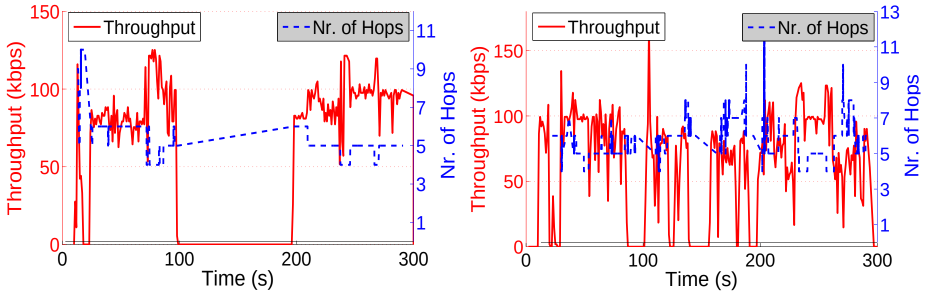


(a) 40N, 1-3 m/s (A) (b) 40N, 2-8 m/s (B)



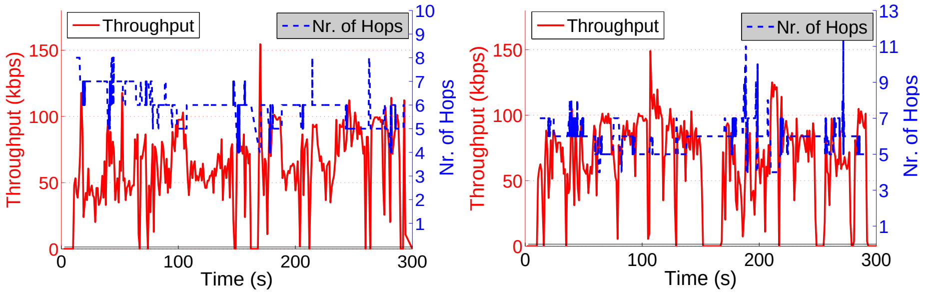
(c) 80N, 1-3 m/s (C) (d) 80N, 2-8 m/s (D)

Figure 7.8: Throughput vs. Number of Hops (Static4)



(a) 40N, 1-3 m/s (A)

(b) 40N, 2-8 m/s (B)



(c) 80N, 1-3 m/s (C)

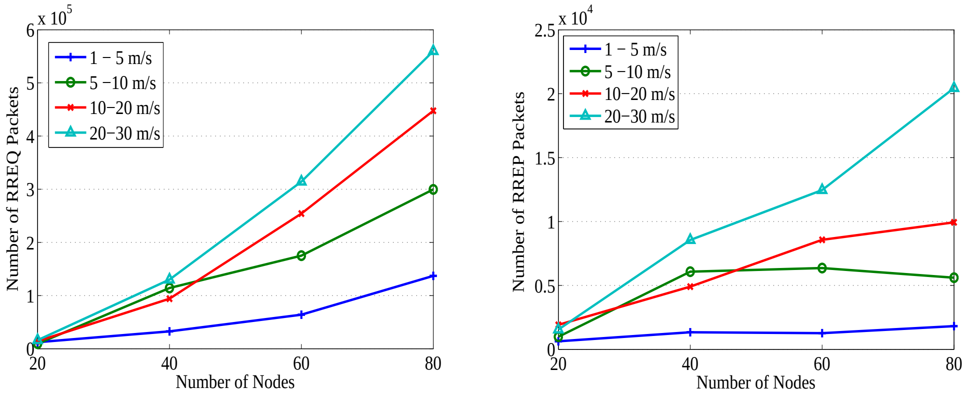
(d) 80N, 2-8 m/s (D)

Figure 7.9: Throughput vs. Number of Hops (Static9)

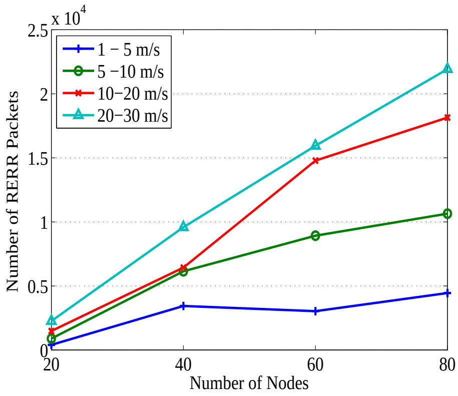
Considering the average values, we can see that for all scenarios the throughput is around 5 times lower than CBR of sent data. For Static2 and Static4 scenarios, as the speed of nodes increases, there is a slight increase in number of hops. Thus, the throughput also decreases. In Static9 scenario, when the speed increases, we see an improvement in number of hops and also in throughput.

The static components (nodes) in this scenario are closer to each other ($424.26m$). When nodes move with a higher speed, the spaces between the static nodes will be covered faster in case of any disconnection. When the network is denser (80 nodes), the number of hops has more oscillations and the average value is higher compared to sparser network (40 nodes) case.

As we can see from Figs. 7.7(a), 7.8(a) and 7.9(a), the disconnections last for longer period of time, because the network is sparser and the nodes need time to recover for this situation due to low speed of movement. In the other cases, the disconnections are recovered faster with AODV “route repair” procedure. In general, the throughput has a lot of oscillations due to route changes, for all cases in all scenarios.



(a) RREQ (b) RREP



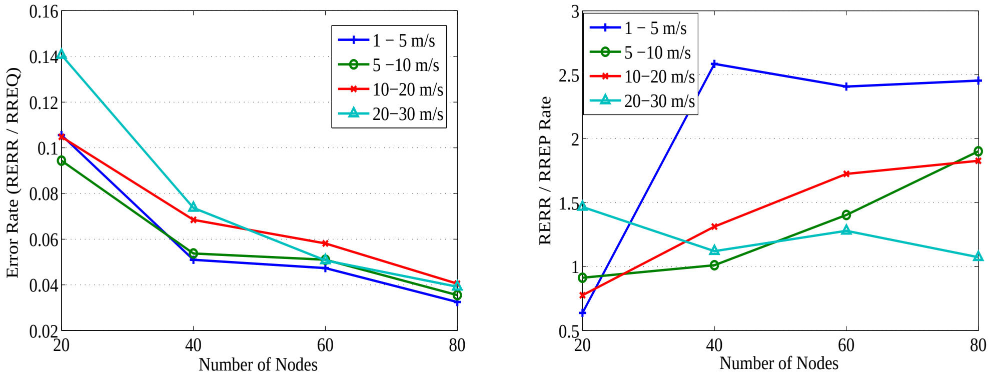
(c) RERR

Figure 7.10: Results for AODV packets.

7.3 Case 3: RREQ, RERR, RREP, HELLO for AODV

In this section, we will present the simulation results for 16 cases, investigating the effects of density and speed of nodes. We show the total number of RREQ, RREP and RERR as well as the rate of RERR packets, in order to understand how is effected the throughput of one-flow communication, which is shown as the average values during 300-second simulation.

In Fig. 7.10, we show the number of each type of route-control packets, as the network becomes denser and the speed increases. As the network gets bigger, RREQ packets are broadcast all over the network, so the number of RREQ increases progressively from a network with 20 nodes to a network with 80 nodes (see Fig. 7.10(a)). We can also notice the increase of RREQ packets, when the moving speed



(a) RERR / RREQ (b) RERR / RREP

Figure 7.11: RERR Packet Rate.

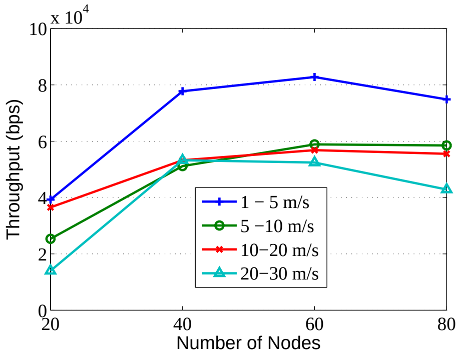
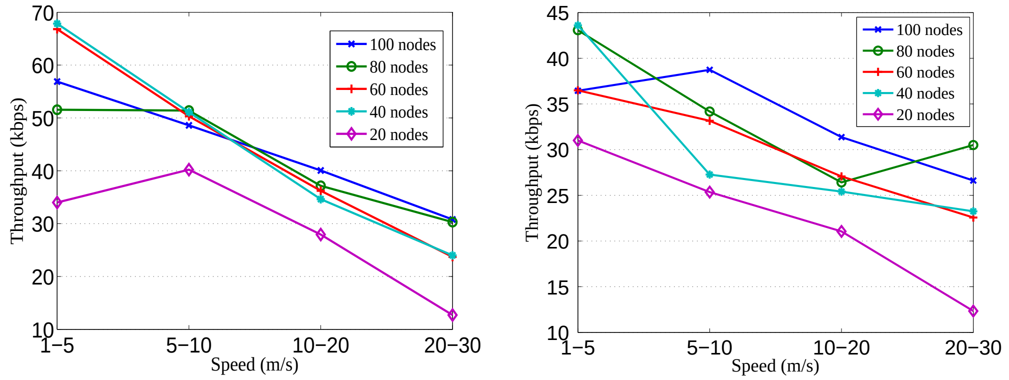


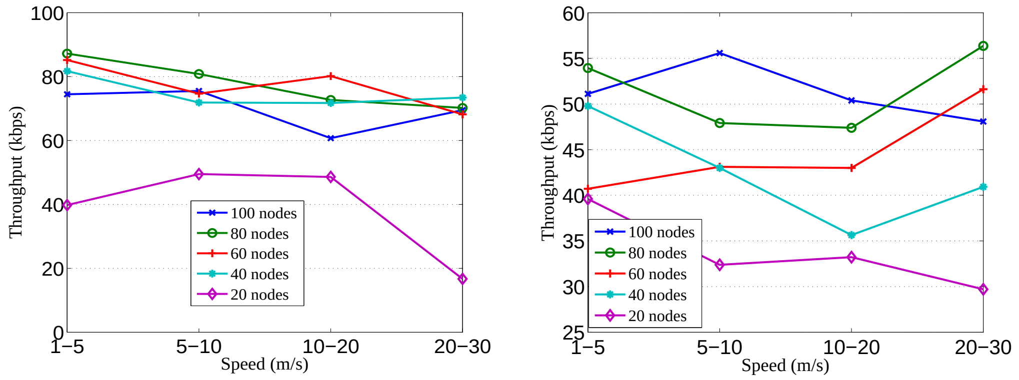
Figure 7.12: Average throughput.

of nodes increases. For higher speeds, the number of RERR packets is also increased (see Fig. 7.10(c)), because of frequent topology changes. If a RERR packet is generated, the source node will request another route. So, the number of RREQ packets will increase. The number of RREP packets, as shown in Fig. 7.10(b), has a slightly different trend. For higher speeds it tends to increase, and for lower speeds it keeps similar values after 40 nodes.

Because we thought RERR and RREQ packets are related to each other, in Fig. 7.11(a), we show the error-request rate of RERR over RREQ. As the number of nodes increases, the rate decreases. An interesting fact is that all the trends for different speeds and different number of nodes are similar, especially for low speeds and high density, where the topology is more stable. On the other hand, in Fig. 7.11(b), we show the error-reply rate of RERR over RREP. As we assumed before, there is no direct relationship between RERR and RREP.



(a) Throughput (Single flow. OFF) (b) Throughput (Multiple flow. OFF)



(c) Throughput (Single flow. ON) (d) Throughput (Multiple flow. ON)

Figure 7.13: Throughput results.

The average throughput values are shown in Fig. 7.12. We can see in general that, for higher speeds, because the topology is highly dynamic, there are a lot of RERR and the throughput is lower. On the other hand, in cases with 40 or more nodes, we notice a similarity between the RREP graphs and throughput graphs. Alike RREP, throughput also stops from increasing for 40 nodes and more. As the number of RREP packets does not increase, it means there are not many available routes found, while the number of RERR continues to grow. The performance of throughput increases slightly from 40 to 60 nodes and then decreases a little when 80 nodes. In this case, 60 nodes create a better coverage than 80 nodes in the given area, because as the network scales, the number of broadcast packets increases, causing a larger overhead.

Then, we activate the HELLO packet function of AODV. We will show the simulation results for single-flow and multiple-flow traffic, in the following. For multiple-flow data, the average throughput values of 4 flows are presented.

The throughput results are shown in Fig. 7.13. Throughput results for multiple-flow communication is shown the average value for all four flows. In general, throughput decreases as the moving speed increases, because the routes become unstable. When there are 20 nodes in the network, the performance is lower, because the area is too big to get covered by 20 nodes. When the number of nodes increases, throughput becomes a little better. When we activate HELLO packet function, throughput values decrease a little in general, but they become more unaffected by the speed of movement, as seen in Fig. 7.13(c). When the network gets denser, the number of control packets increases, and more control overhead is present in the traffic. On the other hand HELLO packets make the system flexible to dynamic changes, when moving speeds get higher. For multiple-flow traffic the average throughput values decrease.

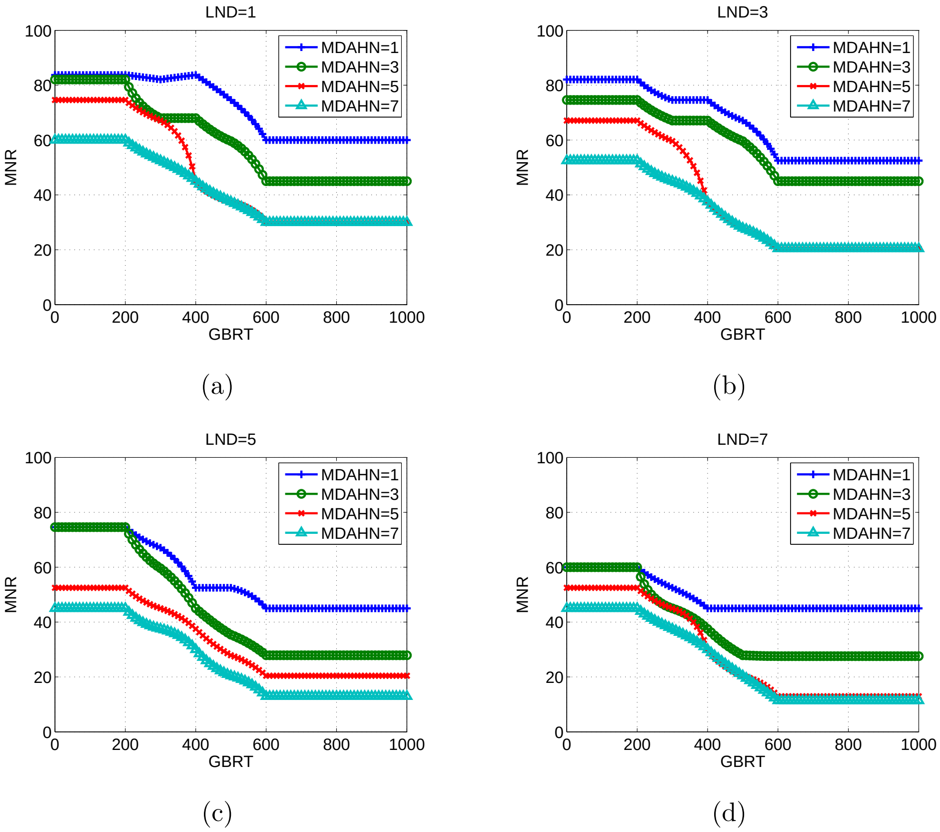
7.4 Case 4: Data Replication

In our simulations we got data for different values of LND and MDAHN. The results are shown in Fig. 7.14. In each figure, in the horizontal axis, it is shown GBRT and in the vertical axis it is shown MNR. Data was taken for 4 values of LND (shown in each figure) and for 4 values of MDAHN (shown in the legend).

In general, we notice 3 zones for GBRT values, according to system behavior.

- Zone 1: GBRT from 0 to 200
- Zone 2: GBRT from 200 to 600
- Zone 3: GBRT from 600 to 1000

In Zone 1, MNR is almost stable. It starts to decrease in Zone 2 and becomes constant on Zone 3. These zones have different behavior when MDAHN and LND change their value. As MDAHN increases from 1 to 7, MNR values decrease constantly. The same results are shown for LND. If LND increases, MNR decreases because a small number of replicas, can cover a dense network better than a sparse network.



(a) (b)

(c) (d)

Figure 7.14: FDRM system results.

For plot lines of MDAHN 1 and 3, we notice that there is a similar trend for Zone 1. This means that, for low values of MDAHN (less than 3), the system requires a lot of replicas in order to satisfy the QoS requirements.

From 400 to 1000 ms of GBRT, the plot lines of MDAHN 5 and 7, have similar trends and MNR have similar values. In this case, where the system requires higher GBRT and MDAHN is more than 5, the number of replicas is low, because they should be enough to satisfy these QoS requirements.

Chapter 8

Conclusions and Future Works

8.1 Conclusions

In this work, we designed and implemented a MANET testbed, in which we implemented three cases in different environments and topologies. In the first case, we use our indoor stairs environment to implement 2 scenarios (VS and VM). We implement 3 other scenarios in our outdoor bridge environment (OBST, OBSM and OBDM). And we use MAC filtering to create linear and mesh topologies in order to test multimedia traffic data in indoor environment. We used throughput, delay and packetloss as metrics for performance assessment of OLSR, AODV and BATMAN routing protocols.

We also implemented a simulation system for testing MANETs, based on NS2 simulator. We considered four simulation cases for different applications of MANETs. In the first case, static source and destination are taken in consideration with two scenarios (ALMOV and SDSTA) In the second case, we increase the number of static nodes in the network, comparing three scenarios (static2, static4 and static9). The third case is concentrated on the performance of AODV, regarding control packets. Finally, a QoS Data Replication framework is presented in the fourth case.

In the following are shown the conclusions.

8.1.1 Experiments

8.1.1.1 Case 1

- Both protocols show a good performance in both STAS and SHIS scenario, for one-hop and two-hop communications.
- For 3 or 4 hops from source (node 4 and 5, respectively), the throughput decreased about 50% compared with DTR, regarding STAS scenario.
- In case of SHIS scenario, when destination was node 4 or node 5, the throughput decreased about 60% compared with DTR.
- Delay is increased after three hops for STAS scenario and after two hops for SHIS scenario.
- In general, OLSR protocol showed better performance than BATMAN protocol.
- The throughput of BATMAN is better than OLSR for SHIS scenario. BATMAN buffers the packets when routes are unstable. However, the buffering increases the delay.
- Regarding 1 → 5 flow, in SHIS scenario, source and destination nodes were closer to each other, so the throughput was higher compared with 1 → 5 in STAS scenario.

8.1.1.2 Case 2

- The movement of the nodes, did not bring any disconnection in the first hop of the communication. The throughput was almost same as DTR and packetloss was almost 0, for all three scenarios.
- When the destination is in the third floor or higher, there are oscillations for both throughput and packetloss, caused by the increased number of hops that the packets had to use to reach the destination.

- When the data flows through 3 or 4 hops to destination, the throughput decreases to less than half of the sent DTR and the packetloss increases to noticeable values. Communication for three or more hops in a MANET testbed becomes difficult.

8.1.1.3 Case 3

- For audio transmissions, the performance was almost the same for both LT and MT topologies. The throughput had a few oscillations.
- The average delay values were under 20 ms and 10 ms, for LT and MT, respectively.
- Packetloss is less than 1 pps for all cases of audio data.
- For video transmissions with higher data rates, the performance decreased as the number of hops increases up to 4 hops in $1 \rightarrow 5$ flow.
- For MT, we could see that the performance for $1 \rightarrow 2$, $1 \rightarrow 3$ and $1 \rightarrow 4$ flows were almost similar, while in case of $1 \rightarrow 5$ flow, the values of throughput fell to around $20kbps$.
- We could see that for audio data there is no difference between LT and MT, but for video data, in MT case the average value of throughput decreased and its oscillations increased.
- The packetloss, is closely related to throughput so it had a similar behavior.
- In LT scheme, routes are static. While in MT scheme, routes change and this decreased throughput and increased packetloss.
- Delay values were higher in the case of LT scheme because of more number of hops.

8.1.2 Simulations

8.1.2.1 Case 1

- When the distance between source and destination is a random function, we can understand the effects of mobility model.

- There are disconnections when there are 4 or more number of hops.
- When moving speed is higher, the topology is more dynamic and the topology information is not updated in time throughout all nodes.
- When the distance between source and destination is a random function, we can understand the effects of mobility model.
- When moving speed is higher, there are more RERRs for AODV nodes. The "Local repair" and new "route request" procedures find different routes, which results in more oscillations in the number of hops and throughput.
- When the node density is high, there are more oscillations.
- The number of hops and throughput are inverse proportional for AODV routing protocol.

8.1.2.2 Case 2

- When the distance between source and destination is fixed, we can understand the effects of mobility model and routing protocol.
- For all scenarios, the average throughput is around 5 times lower than CBR of sent data.
- In Static2 and Static4 scenarios, the performance decreases with the increase of the speed, while in Static9 scenario the performance increases when the speed is increased.
- The number of hops is higher and has more oscillations for denser networks (80 nodes).

8.1.2.3 Case 3

- The movement of the nodes, did not bring any disconnection in the first hop of the communication. The throughput was almost same as DTR and packetloss was almost 0, for all three scenarios.

- When the destination is in the third floor or higher, there are oscillations for both throughput and packetloss, caused by the increased number of hops that the packets had to use to reach the destination.
- When the data flows through 3 or 4 hops to destination, the throughput decreases to less than half of the sent DTR and the packetloss increases to noticeable values. Communication for three or more hops in a MANET testbed becomes difficult.
- When HELLO function is off, the number of RERR packets increases when the number of nodes in the network increases. The number of RERR packets increases in multi-flow traffic case. As the speed of nodes increases, there are more RERR packets in the network for both single-flow and multi-flow cases. The number of RERR packets increases for multiple-flow traffic in the network.
- In general, throughput decreases as the moving speed increases. When there are 20 nodes in the network, the performance is lower, because the area coverage is lower. When the number of nodes increases, throughput improves, for 40 or more nodes. In the case of multi-flow communication the average throughput is lower than the single-flow case.
- The number of HELLO packets in the network is the same for both single-flow and multiple-flow traffic. It is also not affected by speed, but it increases when the number of nodes in the network increases.
- When HELLO function is on, the number of RERR packets decreases.
- Throughput values decrease a little in general, but they become more unaffected by the speed of movement, being helped by HELLO packets information.

8.1.2.4 Case 4

From our MATLAB simulations, we got the following conclusions:

- There are 3 different zones for GBRT values.
- As LND and MDAHN increase, MNR decreases.
- In Zone 1 for MDAHN 1 and 3, the values of MNR are similar.
- In Zone 2 and 3 for MDAHN 5 and 7, the values of MNR are similar and low.

8.2 Future Works

In the following are shown some future aspects of MANETs, which can be inspired by this work.

Testbed Improvement: This work inspires us to improve our testbed with more nodes and spread our experiments in outdoor environment and all over the campus. We would also like to create a monitoring interface, in order to have access to real-time results and accurate node positions. Moreover, an accurate moving mechanism is important to create the same topology in different experimental settings.

Simulated Mobility: During simulation, the mobility model used for node movement has a key influence on the performance of different protocols and algorithms. We would like to create more realistic mobility models, similar to real life cities, campuses or buildings.

Applications of MANET: MANET will be the next technology for creating cheap and autonomous backbones of modern networks. We want to implement the use of MANETs in airspace communications (Air2air network) and in Smart Cities (Internet of Things).

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List of Papers

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1. E. Kulla, M. Hiyama, M. Ikeda, L. Barolli, V. Kolici, R. Miho, “MANET Performance for Source and Destination Moving Scenarios Considering OLSR and AODV Protocols”, Mobile Information Systems (MIS), Vol. 6, No. 4, pp. 325-329, doi: 10.3233/MIS-2010-0106, 2010.

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