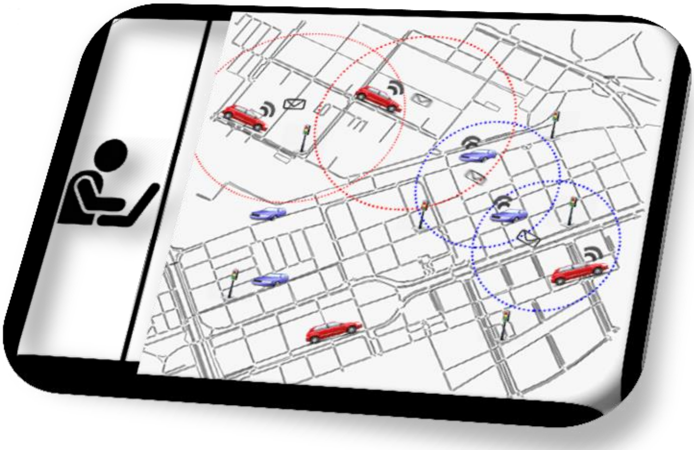
UNIVERSIDAD D SEVILLA

A SIMULATION METHODOLOGY FOR EVALUATING AD HOC COMMUNICATION PROTOCOLS



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Tesis Doctoral
Ingeniería de Telecomunicación

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A mi familia

About me …

I am José Manuel García Campos or simply Jose. I was born in 1989, in Seville. I grew up in the neighbourhood of Parque Alcosa (Seville). I studied there from kindergarten to the high school in “*Lope de Vega”* school and *“IES Pablo Picasso”* high school respectively. After that, I started my university degree in telecommunication engineering in 2007 at university of Seville and I finished this one in 2014, during this period of time I also worked as an intern in a Spanish IT consultant, one year. I began to work in the university of Seville as a researcher at the end of 2014 in *ACETI* research group. In the summer of 2016, I had the opportunity to enjoy a research stay at Leeds Beckett university (Uk). During last two years I was preparing my Phd thesis. Actually, my current research interests include communication protocol simulations for MANET and VANET, mobility models also for VANETs and improve routing protocols based on energy consumption.

This was my formal presentation. Now, I focus on my hobbies and experiences. I consider a lover of sport, especially running. In fact I run many races during these last two years. I even run the Seville marathon in 2016. Among my preferences, the coffee, eat in good company, watch series, walk, enjoy the environment or spend great time with the people who were closed to me …

Agradecimientos

Resumen

El objetivo principal de esta tesis es la mejora de la simulación de protocolos de comunicación en MANETs y VANETs. La simulación es la forma más común para realizar pruebas en este tipo de redes. Muchos trabajos han sido propuestos en este campo. Sin embargo, un conjunto de malas prácticas han sido detectadas como consecuencia de que los investigadores no prestan la suficiente atención en la evaluación de los protocolos de comunicación. Las mejoras propuestas se centran en un conjunto de buenas prácticas que nos permiten obtener resultados de simulación fiables y homogéneos. La idea de esta metodología es evaluar protocolos de comunicación, nuevos y antiguos, bajo las mismas condiciones. Además de esto, podemos evitar la aparición de resultados inesperados los cuales pueden llevar a conclusiones equivocadas. Además, con esta metodología se reducen los tiempos de computación y es posible reproducir los resultados de simulación en diferentes entornos. La metodología se centra en el uso de periodos de medida, la selección de nodos fuentes y destino basada en dos métricas distintas: la disponibilidad del camino y la distancia en cuanto a saltos se refiere entre dos nodos. Otros aspectos de la metodología que ha sido propuesta son, fijar el número de simulaciones para tener una muestra lo suficientemente amplia

y que el tiempo consumido para ello sea el menor posible. Así como, seleccionar el modelo de movilidad y métricas de funcionamiento apropiadas. Para evaluar las características de la metodología se han comparado tres bien conocidos protocolos de encaminamiento, AODV, LAR y DYMO en escenarios urbanos y de desastres. Usando dicha metodología, los resultados son mejorados en términos de media (alrededor del 50%) y también los intervalos de confianza son reducidos. Otro aspecto importante que resuelve esta técnica son los tiempos consumidos para obtener los resultados de simulación. Estos son reducidos a la mitad comparado con no usar la metodología.

Asimismo, también se propone una modificación de la metodología para la evaluación de los algoritmos de broadcasting. En este caso, los nodos fuentes se seleccionan a partir de diferentes características topológicas: el número de nodos alcanzables y la distancia con esos nodos en términos de saltos desde el nodo fuente. Además, se hace uso de periodos de medida y el número de simulaciones también es fijado para que el tiempo consumido sea el menor posible pero que la muestra obtenida sea representativa. Una vez validada la metodología de trabajo, varios algoritmos de broadcast probabilísticos han sido evaluados.

Para testar este marco de trabajo, usamos NS-2 como simulador de red para evaluar los diferentes protocolos de comunicación haciendo uso o no de la metodología propuesta, y C4R y Bonnmotion como generadores de modelo de movilidad. Por último, los resultados de simulación son representados en sus correspondientes gráficas para finalmente ser analizados y confirmar la validez del trabajo propuesto.

Abstract

The main objective of this thesis is to improve the MANET and VANET simulation communication protocols. Simulation is the most common way to test new approaches in this kind of networks. Many works have been proposed in last years in this field. However, a set of bad practices have been detected due to the fact that researchers do not pay attention to how the communication protocols are evaluated. The proposed improvements are focused on a set of good practices in order to obtain reliable and homogeneous simulation results. The idea of this methodology is to evaluate communication protocols, both new and old ones, under the same conditions. Additionally, we can avoid the appearance of unexpected results, which can lead researchers to wrong conclusions about the performance of communication protocols. Furthermore, with this methodology we also reduce the computing time and improve the reproducibility of the communication protocols in different environments. The proposed methodology is focused on using measurement period, selecting source and destination nodes based on two different metrics: the duration of the available path and the distance in terms of number of hops

between them. Other aspects of this methodology are, fix the number of simulation to obtain a representative sample in the minimum period of time, select the appropriate mobility model, the performance metrics to carry out the study and the analysis for a good performance evaluation. To evaluate the proposed methodology features, three well-know reactive routing protocols, AODV, LAR and DYMO are compared in urban and disaster scenarios using and not using the proposed framework. By applying the proposed methodology, the simulation results are better in terms of mean (about 50%) and also the confident intervals are reduced. Another important aspect that solves the proposed framework is the time necessary to obtain those results, which is reduced by the half compared to not using the proposed framework.

A methodology variation of the proposed methodology can also be applied to the evaluation of broadcasting algorithms in disaster scenarios. With this idea, we select source nodes based on different topological characteristics: the number of reachable nodes and the distance with those nodes in terms of number of hops from the source node. In addition, we also use measurement periods and fix the number of simulations to reduce the computing time. After validating the methodology, we evaluate different probabilistic broadcasting algorithms.

The proposed framework is evaluated using NS-2 as network simulator to test the behavior of the different communication protocols, routing and broadcasting, using and not the proposed framework and to identify the advantages in terms of computing time and simulation results. C4R and Bonnmotion are also used as mobility model generators to model an urban and a disaster scenario respectively.

Índice

ÍNDICE DE FIGURAS

1. INTRODUCTION

This chapter introduces the work conducted by this thesis in terms of explaining the motivation, aims, objectives and contributions of the research. Finally, It is included a brief description of the organisation of this thesis.

1.1. Motivation and objective

The innovation in mobile computing technology and the proliferation of communication devices such as: cell phones, laptops, wearable computers, etc., are revolutionizing our way of sharing information. This fact advocates that wireless networks are the most appropriate solution to establish the communication between these devices. In recent years, there has been a tremendous growth in the use of mobile wireless networks and in the access to various mobile applications and services on the Internet. This explosive growth has made wireless communication networks one of the most important areas of research in computer science.

Related to wireless networks, a distinction between infrastructure networks and infrastructureless networks can be done [1]. In infrastructure wireless networks, a fixed, wired backbone infrastructure is available and all communications are directed over this backbone. Examples of infrastructure networks are Global System for Mobile Communications (GSM) [2] and Wireless Local Area Networks (WLANs) [3]. In infrastructureless wireless networks, such backbone does not exist and wireless devices communicate directly with one another through point-to-point connections. An important aspect in infrastructureless wireless networks is the use of multi-hop communications since direct point-to-point connections are only possible between wireless nodes that are in the intermediate radio transmission range of each other.

The deployment of infrastructure wireless networks like a cell network managed by a telecommunication operator is a usual task done regularly by communication companies. However, in those cases where there is no infrastructure or it is not temporally available, the deployment can be difficult or impossible. An example of such situation is a natural disaster. In this case, communications blackout may happen, so it is necessary to re-establish communications quickly to facilitate the work of rescue teams. Therefore, it is necessary to deploy an emergency infrastructure as fast as possible. Another use of this kind of networks is to provide a communication system for pedestrians or vehicles in a city (smart cities). For instance, to avoid collision; it means that drivers can be provided a warning half a second before a possible collision. If a driver gets a warning message on time, the collision can be avoided. Another possible application is traffic optimisation, which means that traffic can be optimised by the use of sending signals like jam, accidents, etc., to the vehicles or pedestrian so that they can choose their alternate paths, and consequently, can save time.

A possible solution to provide communications in the absence of infrastructure is given by ad hoc networks. An ad hoc network is an autonomous system of wireless nodes that cooperatively form a network without any specific administration [4]. The rise of this kind of network is due to the fact that they are self-configurable and scalable networks. Each node in an ad hoc network is in charge of routing information among its neighbours. When nodes are free to move randomly and organize themselves arbitrarily, we refer to them as Mobile Ad Hoc Networks (MANETs) [6]. As an evolution of traditional MANETs, VANETs (Vehicular Ad hoc NETworks) [7] include communications between vehicles (Vehicle to Vehicle, also known as V2V) on the roads and with the road communication infrastructure (Vehicle to Infrastructure, also known as V2I). In dynamic networks such as VANET and MANET, the design and evaluation of routing protocols is of paramount importance. The main reason is that the topology of the network is continuously changing. Therefore, well-known communication protocols designed for wired or infrastructure wireless networks will not perform properly.

Nowadays, simulation is the most common way to evaluate the behaviour of MANET and VANET communication protocols due to the fact that the number of available testbeds is low, and building real testbeds is expensive in term of hardware investment. For this reason, researchers have focused their efforts on testing their new approaches by simulation. In many research works (papers, reports, thesis, etc.), new routing protocols and broadcasting algorithms are proposed, and they are normally evaluated and/or compared by simulation analyses under different conditions, i.e., varying the network congestion or the density of nodes, among others.

However, conducting reliable simulations is not a trivial task and special care should be taken to produce repeatable and representative simulation results. Several studies in the past revealed that researchers have followed bad simulation practices in their studies [8][9][10]. The main reason of such unreliable simulation results is the wrong configuration of simulation parameters. The event-driven network simulators used for the evaluation have many configuration parameters, i.e., propagation models, nodes participating in the communications, transmission ranges, size of scenarios, etc., and simulation results strongly depend on the values given to such configuration parameters.

In general, researchers focus primarily on the design and implementation of their communication protocols; however, they do not pay much attention to how the communication protocols are evaluated. They simply rely on the validity of the network simulator used. This situation leads to an incomplete and unreliable design since the obtained results may not represent the real behaviour of the designed communication protocol. Furthermore, the objective of designing a new communication protocol is to demonstrate that it performs better than other existing approaches in terms of certain performance metrics. Yet, such comparison among protocols should be done fairly; it means that appropriate scenarios and network conditions must be selected in order to infer a statement like “the proposed protocol *A* outperforms the existing protocol *B“*. Unfortunately, in the majority of cases this statement is only valid under certain conditions that normally are selected by the author of the proposed protocol *A* so that he/she could demonstrate the goodness of his/her approach with respect to others.

Regarding the applicability of multi-hop networks, one of the most common applications is disaster scenarios. They can be an appealing alternative communication network to be used in disaster response scenarios. After a disaster situation (flooding, hurricanes, etc.), the communication infrastructure like the cell networks may not work properly due to the damages in cell communication towers. Thus, it could be necessary to deploy a multi-hop network to re-establish the communications and to help the rescue teams to find victims. Before the deployment, new approaches in terms of communication protocols must also be assessed using a simulation analysis. However, disaster scenarios are a very particular application example where movements do not follow typical patterns used in other application scenarios, such as random movements or movements constrained to roads in the case of VANETs. Many previous works have presented mobility models for victims and first responders in disaster areas [11][12]. These works not only model the incident site, which is the region where the disaster actually occurred. They also model other regions such as patient´s treatment area, transport area and others. These mobility models are focused in the transport of patients from the incident site to other regions.

Considering the simulation issues aforementioned, the main objective of this thesis is a simulation methodology that allows researchers to carry out reliable and replicable simulation studies and fair comparisons of communication protocols for both VANETs and MANETs. For this purpose, the thesis focuses on the two main types of communications in multi-hop ad hoc networks such as routing protocols and broadcasting algorithms. The main idea is to solve the detected problems by researchers in the routing protocol and broadcasting algorithm simulations. More specifically, a set of good simulation practices and parameter configuration that guarantee reliable simulation results is proposed. This methodology can be applied to any multi-hop simulation scenario. In this thesis we focus on two of them, urban and disaster scenarios respectively.

1.2. Contributions

From the point of MANET and VANET communication protocol simulations, a methodology to obtain reliable simulation results is proposed. This framework is based on learning from a set of gathered bad practices from the research community and the aim is to control some simulation parameters which can cause unreliable or unexpected simulation results. The proposed methodology includes several aspects. The first one is the selection of source and destination nodes, from now on communication pairs, based on two different concepts: the duration of the path and also the distance in terms of number of hops between source and destination nodes. Another aspect to consider is the importance of selecting the proper mobility model that reflects the real behaviour of the nodes in urban scenarios. Measurement period is another point of the proposed methodology. They are necessary to evaluate the behaviour of the communication protocols, in terms of ensuring that all network and mobility parameters are stabilized. We also take into account the type of analysis in order to decide which analyses we should be carried out for obtaining a good performance evaluation of communication protocols. The selection of performance metrics that better represent an unbiased performance of the communication protocols also plays an important role. Finally, the number of simulations that should be carried out for each data point in the results is also considered. The selection of these simulation parameters is very important to make a fair and unbiased comparison of communication protocols.

1.3. Thesis organization

This thesis is structured in eight chapters. Chapter 1 is the introduction that motivates the research and details the main contributions. The next two chapters contains an overview about different kind of multi-hop ad hoc networks, routing and broadcasting protocols in chapter 2, and tools to simulate multi-hop networks and mobility models in chapter 3. Chapter 4 reviews previous research related to MANET and VANET simulation problems. The proposed framework to obtain more reliable simulation results in MANET and VANET communication protocols for urban and disaster scenarios is presented in chapter 5 and 6, respectively. And finally, chapter 7 includes the conclusion and future works of this thesis.

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2. INTRODUCTION TO COMMUNICATION IN WIRELESS MULTI-HOP NETWORKS

This section begins with an introduction to multi-hop ad hoc networks and their evolution (section 2.1 and 2.2), followed by a review of broadcasting algorithms and routing in sections 2.3.1.

2.1. Wireless multi-hop ad hoc networks

Ad Hoc Wireless Networks have received significant attention over last few years due to its potential applications in a wide variety of situations such as battlefield, emergency relief, etc. It is a special structure of wireless communication network, where communication relies on the cooperation among the nodes following a wireless multi-hop strategy. Therefore, this kind of network does not rely on any fixed infrastructure, and behaves as self-organizing and self-managing network. In these networks, each node is capable of talking directly to other nodes, so access points controlling medium access are not required. The simplest form of self-organizing network is given by single-hop ad hoc wireless networks, which are obtained by interconnecting devices that are within the same transmission range. Many wireless network standards support the single-hop ad hoc network paradigm, i.e., Zigbee, Bluetooth and IEEE 802.11 standard´s family, among others. However, and due to the restricted transmission range of wireless interfaces, in many cases the communication traffic has to be extended over a number of intermediate nodes to facilitate the communication among them, leading to the so called multi-hop ad hoc wireless networks. In this kind of networks, every device acts as a router and as a host.

When nodes are free to move randomly and organize themselves arbitrarily, we refer to them as Mobile Ad Hoc Networks (MANETs) [1]. As an evolution of the traditional MANETs, VANETs (Vehicular Ad hoc NETworks) [2] include communications between vehicles (Vehicle to Vehicle, also known as V2V) on the roads and with the road communication infrastructure (Vehicle to Infrastructure, also known as V2I). In these dynamic networks in which the topology is continuously changing, the biggest challenge is finding the path between the communication end points. It is crucial to analyze how routing protocols deals with the changes in the network topology. Many routing protocols have been proposed and evaluated for both MANETs and VANETs [3].

Ad Hoc networks are quite different to cellular networks, in which the path setup for a call between two nodes is completed through the base station, and each base station covers a certain area. Table 1 details some differences between cellular and Ad hoc networks.

Cellular networks	Ad hoc networks
Infrastructure networks	Infrastructure less networks
Fixed, pre-located cell and base station	No base station and rapid deployment
Static backbone network topology	Highly dynamic network topologies
Relatively friendly environment and stable connectivity	Hostile environment and irregular connectivity
Planned in advance	Self-adapting to changes
High setup costs	Cost effective
Large setup time	Less setup time
No limited resources	Limited resources

Table 1 Cellular vs Ad hoc networks

2.2. Type of multi-hop ad Hoc networks

The multi-hop ad hoc paradigm has evolved over time leading to new types of networks such as VANETs, Delay Tolerant Networks (DTN) and Flying Ad Hoc Networks (FANETs). Next, we describe briefly each type of network, providing also their main applications.

2.2.1. Mobile ad hoc networks (MANETs)

The formal definition of a Mobile Ad hoc Networks (MANET) is a network in which each device is free to move independently in any direction and acts both as a router and host of the information. Regarding their mean features, MANETs are the self-configuring and infrastructure-less networks aiming to support mobility of devices. Each device changes its links to other devices frequently leading to a highly dynamic and changeable topology. Usually, nodes are equipped with a single omnidirectional wireless antenna. Since there is no hierarchy, all nodes are in principle equal, and can function both as end points of data communication, and as routers, forwarding data in a multi-hop fashion. Figure 1 shows an example of MANETs in which the central node acts as router between the two other nodes because they are not in range.

As consequence of the mobility of nodes in MANETs, classical communication protocols used by wired networks are unsuitable for MANETs. Typically, nodes run on battery power. Therefore, designing protocols with special power-saving modes and power management functions are very important. Nodes also have lower capacity than wired nodes. This is why routing algorithms should not abuse of computational power in order not to deplete rapidly the battery of nodes.

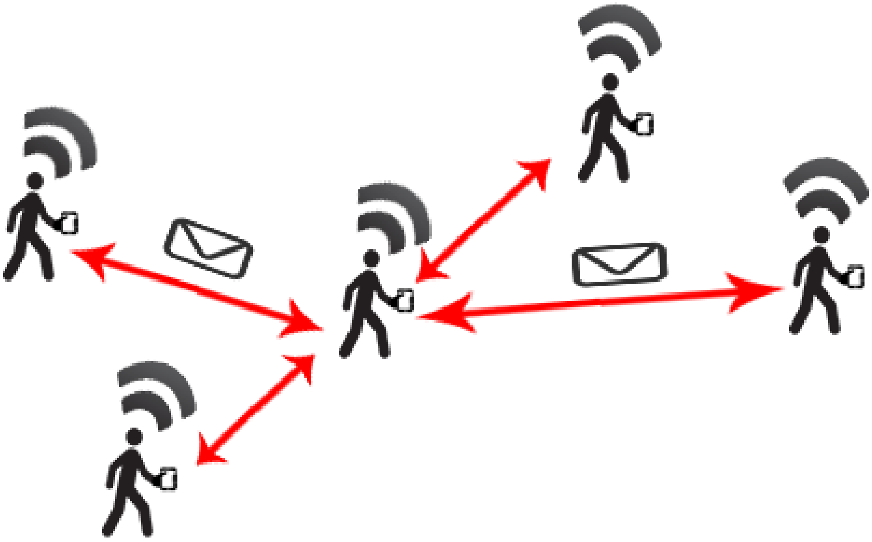

Figure 1 MANET scenario

2.2.2. Delay tolerant networks (DTN)

Delay Tolerant Networks (DTNs) are one of the most interesting evolutions of traditional MANETs [4]. In DTNs, nodes do not require a high connectivity in order to communicate with each other. The transmitted information is not delay-sensitive so nodes follow the carry-store-and forward paradigm in which nodes generate certain information and store it until they have a new opportunity to deliver it. That is, whenever they meet other nodes. Due to this feature, DTNs are also referred as opportunistic networks in the literature, and each encounter between two nodes in the network is seen as a new opportunity to deliver information. In contrast to MANETs, mobility is seen as an advantage for disseminating information in DTNs since the higher the mobility, the higher the number of possible encounters with other nodes.

In DTNs there is no distinction between broadcast and routing protocol based communications. There is only one way of communication between nodes which is used in every new encounter between two nodes [5]. In DTN communications, the information is sent in units called Bundles. When a node generates some information it is split in different bundles, and then, the node waits until encountering another node in order to deliver the information (bundle protocols). Consequently, while MANET routing protocols work on network layer, the bundle protocols for DTNs work on an upper layer namely bundle layer which is between the transport layer and application layer.

2.2.3. Vehicular ad hoc networks (VANETs)

Vehicular networks, or VANETs, are considered as a form of MANETs, deployed to provide communications within a group of intelligent vehicles (Smart vehicles). Vehicles can communicate either with other moving vehicles using V2V communications or with fixed network nodes placed alongside the road (V2I communications), called road-side units (RSUs). RSUs provide moving vehicles with access to an infrastructure network, as well as infrastructure-based services. RSUs can be placed next to the road in regular intervals, or be integrated within existing road infrastructures, e.g. road signs, bridges, or toll gates. Figure 2 depicts an example of VANET involving V2V and V2I communications. This figure shows the case of a closed road and how an alert message is sent out to vehicles so they can take alternative routes.

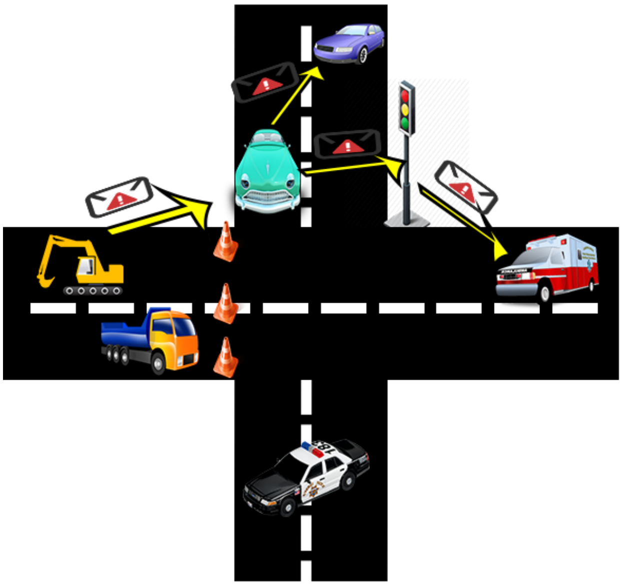

Figure 2 VANET scenario

VANETs are similar to MANETs. Nevertheless, research works and achievements carried out in the field of MANETs cannot be directly applied in the context of vehicular networks since the latter has unique features and specificities. The high mobility of the nodes in VANETs leads to very changing networks. The speeds of VANET nodes are much higher than MANET nodes, so a node can join or leave the network in a short period of time. Network density can also vary from a dense network to uncongested network such as urban and rural areas, respectively. However although the network is dynamic, it may not be completely random because the movement of vehicles is confined to roads and lanes, and this aspect significantly affects the mobility of the network. Another aspect that impacts on the behaviour of the network is the layout of the VANET scenario, for instance, the block size. A city block can be considered the smallest area surrounded by streets. The block size determines the number of intersections in the area, which in turn determines the frequency with which a vehicle stops and changes It movement. It also determines whether nodes at neighbouring intersections can hear each other's radio transmission. Larger block sizes make the network more sensitive to clustering and degrade performance. In the same line, the traffic control mechanisms result in the formation of clusters and queues of vehicles at intersections and subsequent reduction of their average speed of movement. Reduced mobility implies more static nodes and slower rates of route changes in the network. Finally, the speed of the vehicle determines how quickly its position changes, which in turn determines the rate of network topology change. The speed limit of each road also directly affects the average speed of vehicles and how often the existing routes are broken or new routes are established. If the speed of the nodes is high, for instance in motorways, the probability of broken links is higher than in road city centre in which the speed is lower, around 30 or 50 Km/h..

VANETs have the potential to grow at a very huge scale especially in urban areas where intersections and multi-lane roads are frequent. Hence, VANET protocols, especially those based on a dissemination process, have to deal with a large number of possible wireless collisions and interferences between nodes during transmissions. As in MANETs, nodes need enough resources in terms of battery for the installed devices. However, the energy consumption in VANETs is a secondary factor since nodes have enough electrical power. In addition, each vehicle is equipped with an on board unit (OBU) that executes a single or a set of applications and supports a multitude of wireless technologies such as Wi-Fi, WiMax, GSM, Bluetooth, etc. In contrast, data security and privacy stands as a major challenging problem in VANETs. Indeed, wireless communications used in VANETs are very vulnerable due to the fact that attacks can be played without requiring physical access to network infrastructure. Therefore, it is essential to design VANETs as robust as possible and secure them against attacks.

2.2.4. Flying ad hoc networks (FANETs)

They are multi-hop ad hoc networks in which nodes are UAVs (unmanned aerial vehicles). There are two types of UAVs depending on the vehicle architecture: i) fixed-wing and ii) rotary-wing UAVs. The Fixed-wings UAVs [6] are characterized for performing conventional take off and Landing (CTOL) operations like commercial passenger’s planes. Fixed-wing UAVs [7] are not able to hover in a specific position. Therefore, they require maintaining a minimum cruising speed in order to have lift forces.

Due to their flying properties, FANETs have the advantage of avoiding most of the obstacles that other terrestrial robots might find on the ground. This characteristic makes FANETs to be less affected by obstacles in many of their applications. Consequently, communication links suffer less from fading, multi-path propagation and other ground-like disturbances [8].

FANETs usually do not have a fixed topology. However, depending on the applications, different hierarchies and topologies may be needed. Sometimes, FANETs organize themselves in two groups. On the one hand, groups with a high number of UAVs and can be called based level UAVs. This one performs the main tasks related to the mission assigned, such as: extending connectivity in disaster areas, remote sensing, tracking targets, and others. The other group consists of a few UAVs equipped with more powerful communication devices and computing resources. These UAVs create a high level layer for long-range communication and processing purposes.

In general, FANETs are based on communication links established among UAVs, and other links with other higher level networks and/or ground base stations or command centres. Therefore, it is common to find UAVs-to-ground communication links in order to transmit data from the FANET nodes to ground stations and vice versa. However, the communication in multi UAV is either i) in vehicle communications (IVC), ii) airplane-to-airplane (A2A), iii) airplane-to-infrastructure (A2I).

2.3. Communication protocols in multi-hop ad hoc networks

In this subsection will be summarized both types of communications in multi-hop ad hoc networks, broadcasting and routing respectively.

2.3.1. Broadcasting in multi-hop ad hoc networks

Broadcasting is an important dissemination mechanism in multi-hop networks like MANETs, VANETs, and wireless sensor networks WSNs [8]. It is the operation used to transmit data in a one-to-all fashion, whenever a node broadcasts a message; all its neighbors receive it. Among the main applications of broadcasting are i) the discovery phase of routing protocols, and ii) the dissemination of emergency messages in VANETs and disaster scenarios. In Figure 3 we depict an example of the dissemination of broadcasting messages. The simplest broadcasting algorithm is the flooding, where a node (S in Figure 3) sends a packet to all its neighbour nodes in the network. The one-hop neighbours in turn retransmit to their neighbours and so on, until the message has been propagated to the whole network.

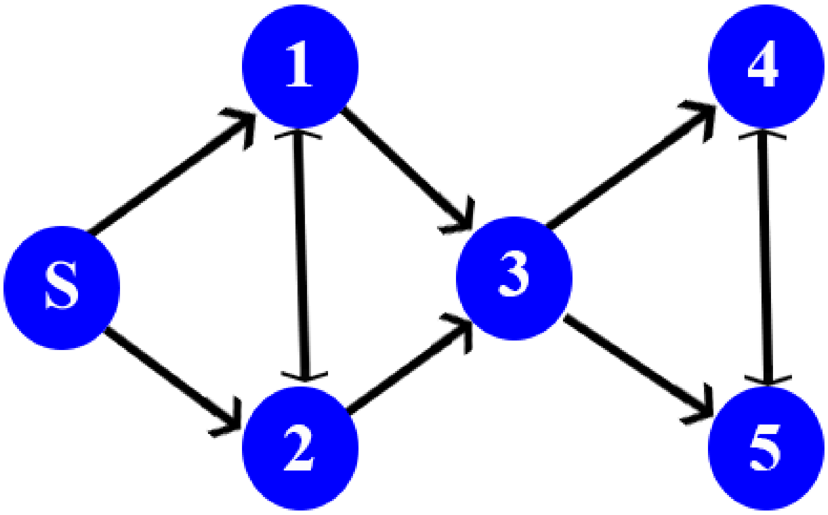

Figure 3 Dissemination of messages in broadcasting algorithms

The goal of broadcasting approaches is to maximize the reachability in the network [9], i.e., the amount of nodes in the network that receive a certain broadcasting message. Some applications and network protocols require that always all nodes in the network must receive a broadcast message; otherwise the protocol will not work properly. For instance, many routing protocols for wireless multi-hop networks assume that in the route discovery phase all nodes receive the route-request message. Although broadcasting is a simple operation, it has attracted the attention of the research community during the last two decades because there is no optimal solution employing only local information of nodes, i.e., the required overhead is high and may not allow the scalability of this approach in networks with higher number of nodes.

2.3.1.1. Classification of the broadcasting algorithms

Broadcasting algorithms can be categorised [11] as i) simple flooding, ii) probabilistic, iii) area-based methods, iv) counter-based methods, and v) neighbour knowledge schemes. Simple flooding is the simplest broadcasting method in which each node retransmits an incoming packet once. Unfortunately, it is inefficient in terms of redundancy, resulting in the well-known broadcast storm problem [12]. In probabilistic schemes, nodes rebroadcast the incoming packets with some probability [12]. This forwarding probability can be calculated using numerous parameters such as density of nodes, distance between nodes, and the speed of nodes, among others. Area-based approaches require nodes to be equipped with a positioning system like the Global Positioning System (GPS) or they should implement a localization algorithm, for instance using the Received Signal Strength Indicator (RSSI), or other alternative measurement systems. Counter-based methods exploit the number of received copies of a given packet in order to estimate the density of nodes and to obtain feedback on the broadcasting process in the node's neighborhood. The basic idea is that nodes do not need to retransmit if a certain number of neighbor nodes have already retransmitted a given packet. Finally, neighbor knowledge methods use topological information in order to select a set of neighbor nodes as potential forwarders.

Another basic classification of broadcasting approaches divides them into two main groups [14]: i) deterministic approaches, and ii) probabilistic approaches. In deterministic approaches a subset of all nodes in the network is selected as optimal forwarders, thus these nodes always forward an incoming packet. This type of broadcasting presents some shortcomings. First, under node mobility conditions, the algorithm used to select the optimal forwarders must determine the nodes belonging to this subset continuously. However, it can be difficult or costly in terms of data exchange depending on the dynamics of the network and the information required by the algorithm. Second, in networks with limited energy resources such as WSN, the subset of selected forwarder-nodes will deplete their energy quickly, resulting in network partitioning. Third, deterministic approaches are more prone to suffer from the presence of malfunctioning nodes and malicious nodes, e.g., in the case that a malicious node is selected as a forwarder.

2.3.1.2. Well-known probabilistic broadcasting algorithms

In this section we summarize some of the most common broadcasting algorithms, which will be also used to validate the proposed simulation methodology.

Flooding [15]: this is the simplest broadcasting method in which each node retransmits an incoming packet once. Unfortunately, it is inefficient in terms of redundancy, resulting in the well-known broadcast storm problem.

GOSSIP [16]: this is the simplest probabilistic approach. In this algorithm, the nodes forward an incoming packet with a fixed probability p, and the probability of not forwarding the incoming packet is 1 – p.

P-persistence [17]: in this algorithm the forwarding probability *p* is determined linearly with the relative Euclidean distance between two nodes *i* and *k* according to the following expression:

$$p = \frac{d_{ik}}{r}, \quad 0 \leq d_{ik} \leq r \qquad (1)$$

In (1), *r* represents the nodes' radio transmission range and d_{ij} the Euclidean distance between nodes *i* and *j*.

Polynomial [18]: the main objective of the polynomial broadcast protocol is to reduce the number of retransmitted packets compared with the p-persistence algorithm. The forwarding probability is obtained as follows:

$$p = \left(\frac{d_{ik}}{r}\right)^{g} \tag{2}$$

The main difference from the p-persistence protocol is the exponent g. The forwarding probability function can be tuned by g. In [18] the authors evaluate the polynomial broadcast protocol with different values of g, such as 0, 1, 2, 5, 10, and 20. They concluded that for a low density network, g = 1 (p-persistence protocol) is the best option to ensure high reachability.

Irresponsible forwarding [19]: this algorithm combines the relative distance between two nodes *i* and *k* and also uses the density of the neighborhood to obtain the retransmission probability. The retransmission probability is given by the next equation:

$$p = \left(1 - F_{x_{ij}}(r - d_{ik})\right)^{1/c} \tag{3}$$

The main idea is that the forwarding probability of a node should be proportional to the probability that there is not node in the distance of r-d_{ik}. It means that there is not a node located at a higher distance from the sender.

2.3.1.3. Applications of broadcasting algorithms

Broadcasting plays an important role in the performance of multi-hop ad hoc networks. Broadcasting is widely used as dissemination mechanism in which a node in the network wants to transmit a message throughout the network, and in the discovery phase of routing protocols. It is also used for other operations such as the maintenance of routes, for example Hello messages in routing protocols like Ad Hoc On Demand Distance Vector routing protocol (AODV) [20] or Dynamic Source Routing protocol (DSR) [21], and for localization system, for example LAR messages in Location Aided Routing protocol (LAR) [22].

2.3.1.4. Stand-alone dissemination technique (All-to-All)

Broadcasting is the main mechanism to disseminate information in all-to-all fashion.

This is the case of spreading information in emergency or disaster scenarios. The main goal is to transmit the same information to all nodes forming the network or at least a target percentage of the network. Notice that it should be done efficiently. It means that the number of broadcasting messages used to reach the target outreach should be as low as possible, and in addition to that, the messages should go along the network as fast as possible since the delay can be an important parameter in the broadcasting-based application.

Although broadcasting is a simple mechanism, it still widely used in multi-hop ad networks. For example in WSNs with limited resources, broadcasting is the main mechanism to transmit the sensed information from the sensing nodes to the central node or sink node.

In VANETs broadcasting is also envisioned to play an important role in order to transmit emergency information in case of traffic accidents. In fact, the MAC layer used in IEEE 802.11p standard defines different priorities for broadcasting messages. The idea is that safety messages have more priority [23].

2.3.1.5. Discovery phase of routing protocols

When broadcasting is used in the discovery phase of routing protocols, the objective is to find a destination or several destination nodes (depending on if it is unicast or multicast routing protocol) in the network. Notice that the objective is slightly different from the previous case (broadcasting as a stand-alone dissemination technique). In this case, a source node does not want to reach every node in the network. Instead, it requires knowing if a route is available to communicate with a target node. Consequently, the dissemination of the broadcasting message should be guided to the destination node. In most of the classical routing protocols for multi-hop ad networks such as AODV, DSR, and DSDV, nodes make use of simple flooding as the broadcasting protocol to reach a destination node from a source node. However, it is well-known that flooding is either inefficiently and costly in terms of number messages exchanged, causing the broadcast storm problem [24]. For this reason, a number of broadcasting algorithms have been proposed to improve the discovery phase of routing protocols [25].

2.3.2. Routing in multi-hop ad hoc networks

Routing is an important issue for communication networks in general and multi-hop networks in particular. Many routing algorithms have been proposed for wired networks and some of them have been widely used. Nowadays routing approaches are prevalent in wired networks. However these routing protocols cannot be used in multi-hop ad hoc networks due to the constant changes of the nodes in the networks, in terms of positions, and rapidly deployable networks that do not need a fixed infrastructure and any central administrator. The central challenge in the design of routing protocols is that they can efficiently find routes between two communicating nodes. In multi-hop networks, routing protocols are responsible for deciding the best (multi-hop) paths to send data across from source to destination. Also, they must be able to deal with the high mobility that often changes the network topology drastically and unpredictably. They are mainly developed to maintain route inside the network, and they do not utilize access points to make connection with other nodes in the infrastructure network and the Internet. Routing protocols can be classified into different categories depending on their properties. In this work we will use two of them [26][27]. The first classification distinguishes between reactive, proactive and hybrid routing protocols. i) In reactive routing protocols, the source initiates a route discovery mechanism to discover a route to the destination node whenever it has data packets to send to the destination node. After discovering the route, the route maintenance is initiated to preserve this route until the route is no longer required or the destination is not reachable. The main advantage of these protocols is that overhead messaging is lower. ii) In proactive routing protocols, they maintain one or more routing tables in every node in order to store routing information about other nodes in the multi-hop ad hoc network. These routing protocols attempt to update the routing table information either periodically or in response to change in the network topology in order to maintain consistent and up-to-date routing information. iii) Hybrid routing protocols combine characteristics of both reactive and proactive routing protocols to make routing more scalable and efficient. Mostly hybrid routing protocols are zone based; it means that nodes are clustered in different zones to make route discovery and maintenance more reliable. Hybrid routing protocols get benefit from the main advantages of both reactive and reactive routing protocols.

A second classification is detailed in Figure 4). Each category is briefly explained in the following subsections.

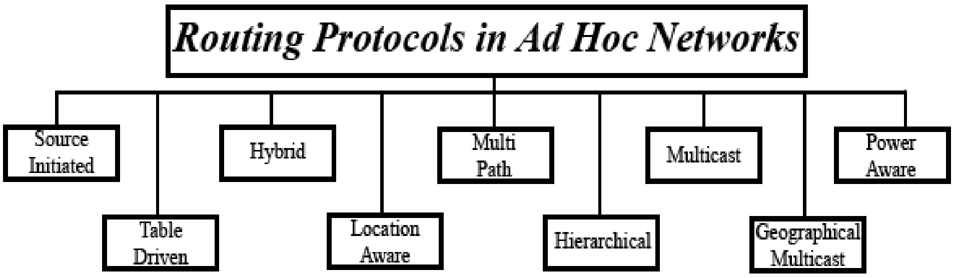

Figure 4 Categories of ad hoc routing protocols

2.3.2.1. Source-initiated protocols

The route discovery phase is initiated when the source requests a route to the destination. The network is flooded with route request packets until a route or multiple routes are created, and then the discovery procedure is stopped.

Name	Acronym	Reference
Ad hoc On-demand Distance Vector	AODV	[20]
Dynamic Mobile On-Demand	DYMO	[28]
Temporally Ordered routing algorithm	TORA	[29][30]
Dynamic Source Routing	DSR	[21]
Labeled Successor Routing	LSR	[31]
Distributed Ant Routing	DAR	[32]

Table 2 Other examples of Source-initiated protocols

2.3.2.2. Table driven

Table driven protocols always maintain up-to-date information of routes from each node to every other node in the network. Routing information is stored in the routing table of each node and route updates are propagated throughout the network to keep the routing information as recent as possible. Different protocols keep track of different routing state information. However, all of them have the common goal of reducing route maintenance overhead as much as possible. These types of protocols are not suitable for highly dynamic networks due to the extra control overhead generated to keep the routing tables consistent and fresh for each node in the network.

Name	Acronym	Reference
Optimized Link State Routing	OLSR	[33]
Dynamic Source Routing	DSR	[21]
Labelled Successor Routing	LSR	[34]

Distributed Ant Routing	DAR	[35]

Table 3 Table driven protocol examples

2.3.2.3. Hybrid

It combines elements of on-demand and table-driven routing protocols. Those areas where the connections change slowly are more amenable to table driven routing while areas with high mobility are more appropriate for source-initiated approaches. With this combination the system can achieve a higher overall performance.

Name	**Acronym**	**Reference**
Zone Routing Protocol	ZRP	[36]
Fisheye State Routing	FSR	[37]
Landmark Ad Hoc Routing	LANMAR	[38]
Distributed Ant Routing	DAR	[39]

Table 4 Hybrid protocol examples

2.3.2.4. Location aware

This scheme assumes that the individual nodes are aware of the locations of all the nodes within the network. The best and easiest technique is the use of the Global Positioning System (GPS) to determine the exact coordinates of these nodes in any geographical location. This location information is then utilized by the routing protocol to determine the routes.

Name	**Acronym**	**Reference**
Location Aided Routing	(LAR)	[22]
Distance Routing Effect Algorithm for Mobility	DREAM	[40]
Greedy Perimeter Stateless Routing	GPSR	[41]
Adaptative Location Aided mobile ad hoc network Routing	ALARM	[42]

Table 5 Location Aware protocol examples

2.3.2.5. Multi path

More than one route is created between source and destination nodes. The main advantage is that the bandwidth between links is used more effectively with greater delivery reliability.

Name	**Acronym**	**Reference**
Ad hoc On-demand Multipath Distance Vector routing	AOMDV	[43]
Neighbor Table Based multipath Routing	NTBR	[44]

Split Multipath Routing	SMR	[45]
Scalable Multipath On-demand Routing	SMORT	[46]

Table 6 Multi path protocol example

2.3.2.6. Hierarchical

Hierarchical ad hoc routing protocols build a hierarchy of nodes, typically through clustering techniques. Nodes at the higher levels of the hierarchy provide special services, improving the scalability and the efficiency of routing.

Name	Acronym	Reference
Hierarchical State Routing	HSR	[47]
Core-Extraction Distributed Ad hoc Routing	CEDA	[48]
Hierarchical Landmark Routing	H-LANMAR	[49]

Table 7 Hierarchical protocol examples

2.3.2.7. Geographical multicast

This one is a variant of multicast where the goal is to route the packets coming from a source to destinations located within a specific geographical region.

Name	Acronym	Reference
Geocast Adaptative Mesh Environment for Routing	GAMER	[50]
Geocasting in mobile ad hoc networks	GeoTORA	[51]

Table 8 Geographical multicast protocol examples

2.3.2.8. Power aware

These protocols make the routing decisions dependent on considerations of the available energy of the nodes. These considerations can be significantly more complicated than simply finding the route with the lowest energy consumption.

Name	Acronym	Reference
Device and Energy Aware Routing	DEAR	[52]
Minimum Energy Hierarchical Dynamic Source Routing	MEHDSR	[53]

Table 9 Power Aware protocol examples

2.3.2.9. Multicast

It is the simultaneous transmission of data from one sender to multiple receivers. For instance, audio-video teleconferencing, real time video streaming and the maintenance of distributed databases are examples of this kind of protocols.

Name	Acronym	Reference

Dynamic Core based Multicast routing	DCMP	[53]
Adaptive Demand-driven Multicast Routing	ADMR	[55]

Table 10 Multicast protocol examples

2.4. References

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3. STATE OF ART OF SIMULATION OF MULTI-HOP AD HOC NETWORKS

In this chapter, the main components and tools typically used to simulate multi-hop networks are presented. It includes the network simulator used in this thesis and a list of other simulators with their main features. Section 3.2 describes the mobility model generators used for this work while section 3.3 details some other mobility models specifically used for MANETs and VANETs. Finally, the workflow followed to simulate this kind of networks and some simulation problems detected by researchers are listed in section 3.4.

3.1. Network simulators

Network simulators play an important role in the design of ad hoc wireless networks. Simulation tools are very useful to test lower communication layers such as MAC and network layer (MAC and routing algorithms). Although many network simulators are available, most network simulators are event-based simulators, which mean that the main output of these simulators is a list of events occurred during the simulation time. Depending on the target network, the simulator are divided into three groups, network simulators for Mobile Ad Hoc Networks (MANETs), network simulators for Vehicular Ad Hoc Networks (VANETs), and network simulator for Wireless Sensor Networks (WSNs). According to the availability of the network simulator, they can also be classified as open source network simulators and commercial network simulators. Open source simulators are freely available so they are appealing for research and education communities. Notice that commercial simulators sometimes offer free versions for educational and research purposes. The final selection of a network simulator depends on many factors such as the final application, the programming skills of final users, usability, cost, included protocols, and so on. The selection of the appropriate network simulator is a crucial task. In this section is detailed the features of NS-2, which is the used network simulator to test the proposed methodology in this thesis. There are some other network simulators that are categorised into different groups. Table 11 list some of them as well as their main features.

3.1.1. Network simulator 2 (NS-2)

Network Simulator 2 (NS-2) was developed as a variant of REAL network simulator in

1989. Later in 1995 the development of NS-2 was supported by DARPA through VINT project. Currently, NS-2 [1] is by far the standard simulation tool for evaluating multi-hop ad hoc networks together with its evolution NS-3. It is an open source discrete event simulator [1]widely used for education and research purposes and capable of simulating wired as well as wireless networks. In NS-2, arbitrary network topologies composed of routers, links and shared media [2] can be defined. The physical activities of the network are processed and queued in form of events, in a scheduled order, and stored in an output file. However, the simulation is not real time, so NS.-2 is considered a virtual simulator [2]. The core of NS-2 is written in C++, but the user interface is configured by scripts in Otcl, the object oriented version of Tcl. The use of Otcl can be seen as an importance advantage since experiments can be easily described and reproduced by writing scripts in Otcl. Basically, NS-2 provides two outputs, 1) a graphic simulation thanks to NAM simulator that allows the users to visualize the deployed networks and 2) a trace file which includes the list of events occurred during the simulation time. This trace file contains detailed information on the events so the analysis of such log file is necessary to study the behavior of the new approach.

The main problem of NS-2 is its poor scalability when inserting new models. In fact, developing new models for NS-2 is not easy task. However, new models have been developed along the years. For instance, new MAC protocols, routing protocols and propagation models available.

Another limitation of this simulator lies in the functions and procedures used to model the PHYsical (PHY) layer and the propagation channel. This limitation becomes relevant when the simulation scenario has to include advanced antenna techniques, such as smart antenna systems, since the evaluation of the benefits of this technology on the performance of the network is strictly related to a reliable estimation of the actual antenna gain and of the channel conditions.

3.1.2. Other network simulators

In this subsection is list a set of common network simulators and some of their characteristics (see Table 11)

Name	Features
NS-3 [1]	Open source simulator Written in C++ and Python Limited scalability The protocol entities are designed to be closer to real computers It supports the incorporation of more open-source networking software Support simulation for TCP, UDP, ICMP, IPv4, P2P and CSMA Much more flexible than other simulators
Omnet ++ [3]	Open source simulator Written in C++ Enough scalability It provides infrastructure and tools for writing simulations Modules can be connected with each other via gates and combine to form compound modules It can be run under graphical and command-line interfaces It supports parallel distributed simulations It does not offer a great variety of protocols
Glomosim [3]	Open source simulator Written in C Large scalability It is a library-based sequential and parallel simulator It allows the simulation scalability to simulate networks with a hundred and thousands of nodes It supports almost al the OSI layers

	It provides modular simulation for protocols
Groovenet [5]	Open source simulator Written in C++ Large scalability It is a modular event-based simulator. It can support thousands of moving and communications. It incorporates mobility, trip and message broadcast models over a variety of link and physical layer-communication models It provides well-defined graphical user interfaces that make easy to add different networks models It implements multiple rebroadcast polices to investigate the broadcast storm problem A defined graphical user interface is defined
Nctuns [6]	Open source simulator Written in C++ Medium scalability It simulates various protocols and networks Realistic network traffic can be generated The performance of any real-life application can be easily evaluated The manipulation of every node has to be done node by node
Opnet [7]	Commercial simulator. Written in C and C++ Large scalability Modelling, simulating and analysis are the main functions Fast discrete event simulation engine

	Customizable wireless modelling It does not allow much number of nodes within a single connected device Simulation is inefficient if nothing happens for long periods

Table 11 Available network simulator feauters

3.2. Mobility model simulator

Mobility models are normally included into network simulators. However, several mobility generators have also been developed in recent years [8][9][10][11]. These mobility generators provide trace files that contain information about mobility of nodes during the simulation time. Such trace files are exportable so they can be integrated into different network simulators. Consequently, mobility generators are developed in parallel to network simulators. The number of mobility model generators is high but this section is focused on the ones used in this thesis.

3.2.1. Bonnmotion

This is an open source mobility generator [12] developed within the Communication Systems group at the Institute of Computer Science IV of the University of Bonn (Germany). It is written in Java and supports many mobility models such as Random Waypoint mobility model, Manhattan grid, Gauss –Markov model, Reference Point Group mobility model, and Disaster model, among others [13][14]. The simulation scenarios are defined by command lines. In addition to the movements of the nodes in a certain scenario, Bonnmotion also defines the size of the scenario, the number of nodes, their speed, the duration of the simulation and how many seconds we want to skip in order to avoid the transitory period of the movement of the nodes. The mobility models can be exported to the following simulators: NS-2, GlomoSim/QualNet, COOJA, MiXiM and One. BonnMotion can also import mobility files with GPS exchange format. With regard to post analysis tools BonnMotion provides other applications for statistical analysis of mobility models, link analysis, and scenario visualization.

3.2.2. Citymob for roadmaps (C4R)

C4R is a simulation tool, which allows simulating vehicular traffic in different locations using real maps [15]. C4R has been implemented using the Java programming languages, and it is distributed under the GNU/GPL license.

C4R has been proposed to simulate more realistic vehicular scenarios based on real roadmaps from all over the world. It relies on both OpenStreetMap [16] tool to get the real roadmaps, and SUMO [17] to generate the vehicles and their movements within these scenarios. It constrains vehicle movements to the streets defined in the roadmap and it limits their mobility according to the vehicular congestion and traffic rules. The vehicle movements are defined according to the selected mobility model. C4R provides some mobility models, such as: Krauss [18], Krauss modified [19], Wagner [20], Kerner [21] among others. C4R allows users to visualize simulations; they can visualize mobility traces once they are generated.

3.3. Mobility models

The mobility model describes the trajectory followed by the nodes during the simulation time. It is designed to describe the movement pattern of mobile users, and how their location, velocity and acceleration change over time. The mobility patterns play an important role in determining the protocol performance. This subsection summarizes the most used mobility models for multi-hop ad hoc networks. We divide this section into two parts: MANETs and VANETs mobility models due to the fact that we evaluate the proposed methodology in this thesis for both scenarios.

3.3.1. MANET mobility models

The movements of individual nodes at the microscopic level, including node location and velocity relative to other nodes, are the most important elements of a mobility model. These factors directly determine when the links are formed and broken, since communication is peer-to-peer. Figure 5 shows a categorization of various mobility models into several categories based on their specific mobility characteristics.

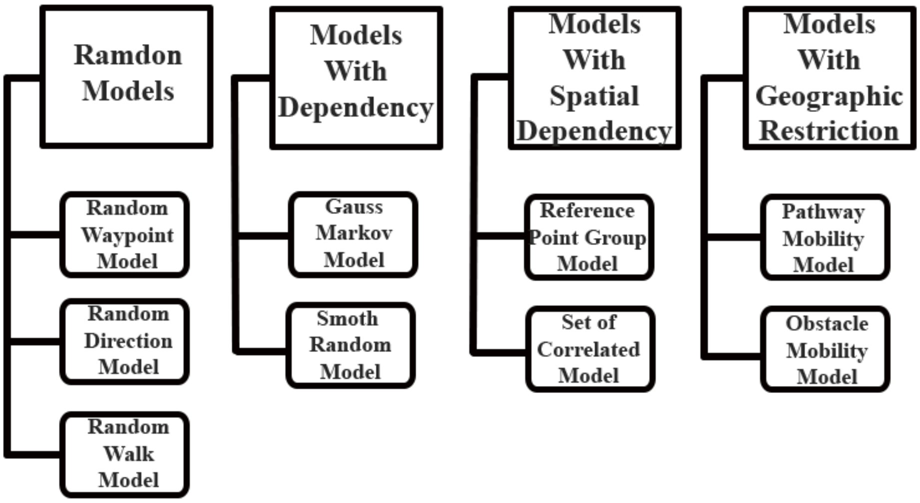

Figure 5 MANET mobility models

Mobility models where nodes do not follow any pattern of movement belongs to the category of *random model* [22][23][24]. When the movements of mobile nodes is likely to be affected by its previous history, the mobility model is known as *mobility model with dependency or with temporal dependency* [25][26]. When nodes tend to travel in a correlated manner, the resulting mobility model is called *mobility model with spatial* *dependency* [27][28]. Finally, another mobility model is the *mobility model with geographic restriction* [29], where the movement of the nodes is bounded by streets, freeways or obstacles.

3.3.2. VANET mobility models

The development of modern vehicular mobility models can be classified into four different classes. This classification is illustrated in Figure 6.

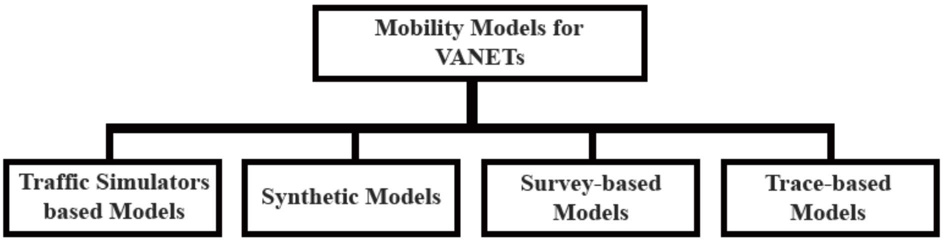

Figure 6 VANET mobility models

In the traffic simulator based models the traces are extracted from a detailed traffic simulator [30]. The models are made by refining the synthetic models and through an intense validation process using real traces or behaviour surveys. These realistic vehicular movements can be modelled by mathematical equations, and we refer to them as synthetic models [31][32][33]. In the survey-based case [30], they represent an important source of macroscopic mobility information. Finally, in traced-based models [30], the mobility patterns are generated from real mobility traces instead of developing complex models and then validating them.

3.4. Methodology for the validation of communication protocols

The evaluation of the behaviour of communication protocols, i.e., routing and broadcasting, in multi-hop networks relies on two main components. First, a network simulator, which is in charge of generating all network components, i.e., the nodes, connections, propagation models, setting the communication protocols, etc. The aim of a network simulator is running simulations on the computer. Normally, the network simulators are event-driven simulators since they consider only discrete times in which the main events of the network occur. The behaviour of the network can be then calculated either by applying mathematical formulas to network entities interconnections or by capturing and playing back observations from a production network (events). Second, there is a mobility model generator in charge of generating the mobility patterns that nodes will follow. Such mobility model depends on the target application of the network, i.e., if the nodes emulate cars, they should move like cars in an urban scenario.

The most widely used frameworks to evaluate the performance of communication protocols are described next along with some of the problems researchers have detected regarding simulations.

3.4.1. Working methodology

The evaluation of MANETs and VANETs routing protocols by simulation is the most common approach for testing the protocols performance so far, because real experimentation in multi-hop ad hoc networks is costly in terms of hardware requirements [34][35]. Testing routing protocols with real MANETs and VANETs prototypes require a high number of wireless devices and there are only a few available testbeds in the world [36]. Therefore, conducting reliable simulation studies is an important requirement to validate the performance of routing protocols for VANETs and MANETs.

The general common working methodology used by researchers to evaluate their new approaches is shown in Figure 7.

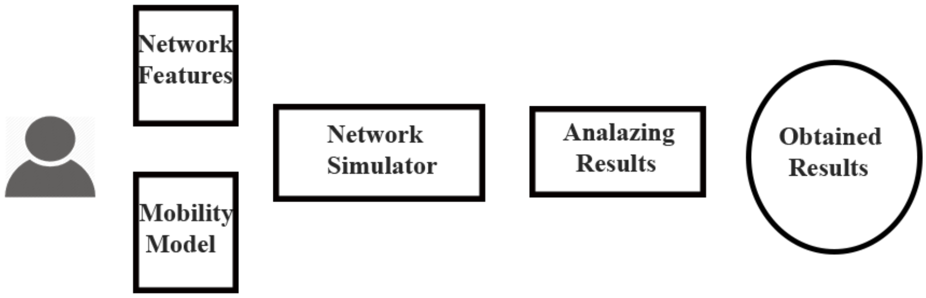

Figure 7 Working methodology

The parameters of the network are set by the user i.e., number of nodes, propagation model, MAC standard, routing protocol, etc. (Networks Features in Figure 7).The mobility model is also selected by the user, depending on the target application of the network.

After developing new communication protocols or improving some features of previously proposed protocols, researchers need to test their new approaches. As a prior step, researchers model the network with an initial position of nodes and select the parameters of the simulation such as the number of nodes or communications, the propagation model, the queue node size, MAC standard, among others. Finally, nodes move around following the selected mobility model.

Once the simulation is completed, the performance of the communication protocols is assessed using some performance metrics such as throughput, packet delivery fraction, end-to-end delay, among others for routing protocols; and reachability, save rebroadcast, and delay, among others for broadcasting protocols.

Although they are the most common performance metrics to evaluate the performance of the communication protocols, there are more of them, and even new performance metrics can be proposed. In fact, some new metrics are proposed in this work. As a rule, the performance metrics provide an idea about the behaviour of the network in terms of congestion, number of delivery packets, etc.

These metrics are not provided directly by the network simulator. Consequently, obtaining them requires processing the output file of the network simulator, which is a complex file with many code lines (one for event occurred during the simulation time). In general, researchers use computer languages such as Python, Perl, Matlab, etc., to parse the output file for obtaining the corresponding metrics as numerical results.

In order to guarantee the reliability of results, researcher must run several simulations to obtain reliable statistics such as the mean value and the dispersion of the output metrics, but maintaining the conditions of the simulation. One strategy followed by researchers to maintain the same conditions and obtaining a richer variety of results consists of varying the communication pairs while keeping the network configuration and the mobility model. The idea is to average the results of several similar scenarios to obtain the output statistics. Following this strategy, the results of several simulations can be averaged and statistically analysed.

3.4.2. Simulation problems

Simulations of multi-hop networks like MANETs have suffered from credibility problems for the last decades [37], mainly because of bad simulation practices conducted by the research community. This lack of credibility is also observable in VANET simulations since most MANET routing protocols researchers are also working on VANET routing protocols design [38].

The main problems found by the researches until now are: i) High dissimilarity among the simulation scenarios. It means that parameters such as size, density and mobility are selected in a different way in each simulation. Consequently the obtained results can be very different and dispersed. ii) The data collection is not properly carried out for a statistical analysis. For instance: the evaluation of the performance metrics starts at the beginning of the simulation time but it may happen that the transmission of the application packets, and in consequence the routing packets, do not initiate at that moment. This desynchronization issue can cause unexpected results when the statistical analysis is applied. iii) There are a high number of network simulators available. The same scenario simulated with different network simulators can lead to different results. The network simulators are written in different computer languages and with different configuration parameters for important parameters such as communication protocols, propagation models, etc. These parameters can cause important differences in the simulation results. iv) The selection of the source and destination nodes is usually done in a random way. The random selection can cause pairs where the communication path is not available or only available during a short period of time. These undesirable effects could deteriorate the averaged performance. v) The establishment of communications among source-destination nodes can start at different times, so some communication pairs could have more time to transmit data packets than others, introducing also some distortion in the final results.

The influence of such practices in the simulation can lead to unexpected or unreliable results. It is even possible that the proposed communication protocols can even have better results than the ones obtained by simulation just because the sources of uncertainties were not fixed previously to run the simulations. Therefore, the simulation results will not reflect the real behaviour of the network, which is the main purpose of conducting simulation studies.

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4. STATE OF ART OF COMMUNICATION PROTOCOL SIMULATION PRACTICES

One of the pioneering works highlighting the importance of conducting reliable simulations in multi-hop ad hoc networks can be found in [1]. The authors report the bad practices followed by researchers in a high number of simulation studies for MANETs. The main findings of this study are, i) there is a high dissimilarity among the simulation scenarios in terms of density, size of the scenarios and mobility, and all of them impact significantly on the obtained simulation results. As a solution for the dissimilarity in the simulation scenarios, the same authors provide in [2] a mechanism to generate standard scenarios for MANETs based on the number of nodes and the size of the scenarios. However, this mechanism is only valid for random waypoint mobility model ii) the mobility of nodes do not model real scenarios since most studies use the random waypoint mobility model, which has been reported to be harmful for simulation studies [3]. It is still the most used mobility model, but it does not produce realistic movement for applications such as human walks [4]. iii) The execution of the simulations and data collection are not properly carried out for a statistical analysis. For instance, the standard formulas for mean and variance are being used without ensuring the data is independent and identically distributed. iv) Changes can be made in the core of the used network simulator. For instance: to add new features or modify some characteristics which will be used to develop new approaches. They have to be checked. However, in many cases researchers do not do that and they build their new developments over mistakes. v) The suitable variable definition. In the network simulators many variables are set by default. However, they can change from one version to another one and it can cause some differences in the simulation results. For that, it is necessary to fix all the parameters to avoid discrepancies between the obtained simulation results by different network simulator versions. vi) Bad metric collection. It means that the performance metrics are not measured properly. There are others bad practices collected in this work [1], but they happen with lesser frequency, such as not identifying the number of simulations and not plotting the confidence intervals in the graph results. In [5], the authors also review the main issues in MANET simulations studies. Additionally, the authors put in evidence the discrepancies in the obtained simulation results from different network simulators. Moreover, they indicate an issue related to the traffic pattern generation and its impact in the obtained simulation results. In general, an easy and unrealistic traffic model is used, Constant-bit-rate (CBR), but the traffic generation level affects the simulation by determining how a given routing protocol will operate under various traffic loads. For that, in [5] is recommended to use traffic generators based on intended applications. Also related to the traffic patterns, in [6] the authors evaluate the performance of several well-known routing protocols with different traffic patterns. They highlight the impact of the repetition of the source nodes in the communication pairs. Another pitfall detected in many routing protocol evaluation works is the use of inappropriate radio models [5] that do not model realistic environment. However, there are some of them that provide more realistic approaches, for example, the two-ray ground and the shadowing models [7]. In a more recent work presented in [8], the authors state that there are still a high number of simulation studies about routing protocols for multi-hop ad hoc networks that do not follow good simulation practices. Among the bad practices described in [8], the authors underline the random selection of source-destination pairs in the traffic patterns as an issue for the evaluation of routing protocols. The authors in [9] highlight the importance of waiting for the mobile nodes to be positioned in their optimal positions. It means that there are many mobility models that consider that all nodes begin in the same position and after some seconds they reach the expected positions. However, during that period of time the behaviour of the network should not be included in the evaluation as it can cause unexpected results. They name that problem as the initial transient problem. Related to VANETs simulations, in [10] is shown the parameters that affect the evaluation of broadcast warning message dissemination. The authors highlight five: i) the topology, they propose to use realistic scenarios instead of easy layouts such as highways or Manhattan style maps. ii) Radio propagation model. They concluded that most of the works do not use radio propagation models. This means that the effect of existing obstacles is not considered. For instance, the effects of building are not modelled. iii) Communication standard, in general it is used 802.11p. iv) Mobility model. They highlight the importance of selecting mobility models that are able to emulate the behaviour of drivers. v) Simulator used. They concluded that the number of VANETs simulators is higher but they are not scalable and they are not easy to use. Apart of showing the main problems found in VANETs previous work related to the dissemination of messages, they also study the behaviour of different broadcast schemes that take into account the detected problems. Many works have been proposed in which are evaluated different performance metrics which measure different features of the communication protocols. In [18] the authors evaluated three well-known routing protocols varying the number of nodes. However, they also follow some of the detected bad practices. For instance they do not address the propagation model, they do not depict the confidence intervals, the source and destination pairs are not selected and unexpected results also appear in the simulation results. One of detected problems in previous research work was the use of unrealistic traffic patterns, the most common one is the use of CBR. In [19] is used FTP and TELNET as traffic pattern and it is also studied the behaviour of three different routing protocols. The authors concluded that AODV shows the best performance for FTP and TELNET. In order to evaluate the behaviour of the routing protocols when the congestion of the network increases, in [20] the authors proposed vary the number of source and destination nodes but they followed one of the detected bad practices, the selection is done randomly, among others. Such as: random waypoint mobility model is used as mobility model or the propagation model is not showed. In this study, they concluded that the best performance results are achieved under low traffic load and depending on the measured performance metric, the best routing protocol will be different.

In order to quantify the bad practices followed by the research community, which have been also listed in this section, we have studied previous research works in which the performance of different communication protocols were evaluated. Both routing and broadcasting have been considered. Among all detected bad practices, we only depict in Figure 8 four of them. More especially, we study the mobility model, the propagation and the traffic model, and also the source and destination nodes selection. Figure 8 shows the obtained results from twenty five different works.

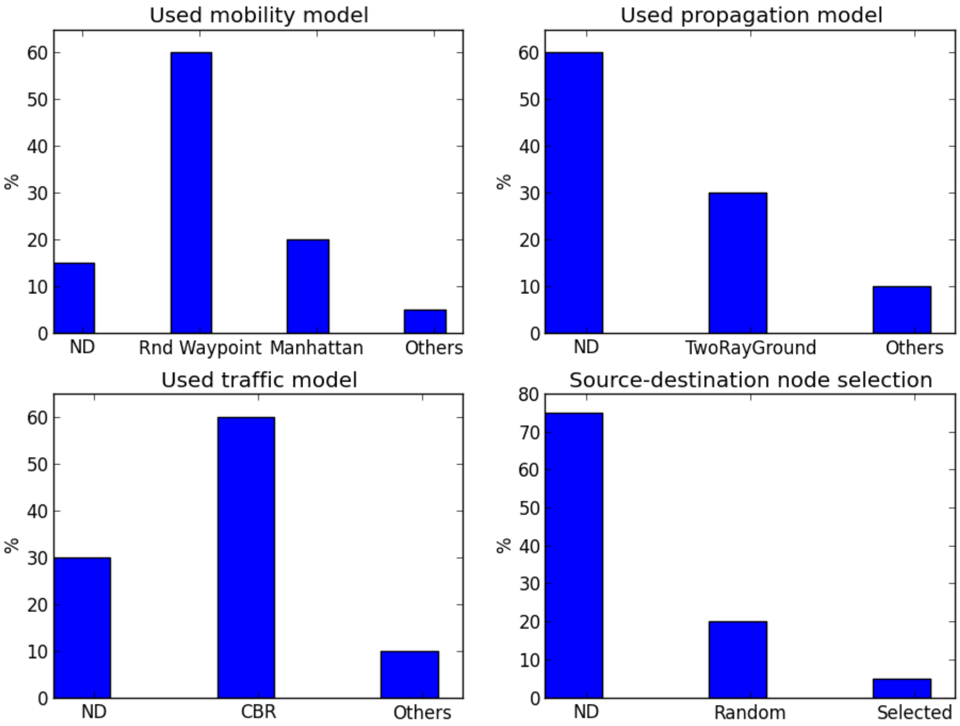

Figure 8 Bad practices quantification

As we can see in Figure 8, the Random Waypoint mobility model is the most common mobility model in spite of being the worst of them, because it does not model real movements. Also and related to the mobility model, there are some cases (about 15%), in which the mobility used is not explicitly addressed. Without this information it is impossible to reproduce the same study in case other researchers are interested. The same happens with the propagation model, which is not identified in many research works, about 60%. CBR is classified as an unrealistic traffic model [11]. However, in most of the studied research work is used, about 60%. Finally, in most of them, the authors do not indicate how the source and destination pairs are selected, and only in one of them they were selected based on some topological features. Summarising this brief study, the most common error is that the researchers do not show used simulating parameters, or even worse, they do not take into account these aspects when they prepare their simulations. Apart from these aspects (see Figure 8), we also analyse other points aforementioned as bad practices. For example, the confidence intervals in the performance metric graphs are not plotted, only in a small number of simulation works. According to our results obtained, they are plotted in 30% of the studied works.

Another crucial aspect in simulation works is the time necessary to obtain the simulation results. In statistical terms, the more trials, the more representative the results obtained. However, increasing the number of simulations strongly impact on the time consumption. For this reason, it is necessary to balance the simulation time and the number of simulations to obtain reliable results. There are other factors that can also affect the simulation time. In [12], the authors show the importance of three different aspects such as, the used routing protocol, the dimension of the scenario and the transmission range. They showed in terms of graphical results that these factors have to be taken into account in order to reduce the consumed time.

As the research progresses from relatively simple systems composed of several nodes connected to a wireless access point to large systems, which might be composed of thousands of nodes, the size of the simulation problem also becomes so large that it clearly exceeds the capabilities of a single machine. In this line, network simulators such as NS-2 cannot be used for this purpose. To cope with this problem, parallel network simulation techniques have been considered. Parallel discrete event simulation reduces the overall execution time by parallelising the execution of the simulation on multiple processors. There exist several parallel network simulators [13][14][15]. Most of them rely on look ahead, which is the ability to predict the earliest time of messages that can be generated in the future. Usually, the look ahead value in a parallel network simulation is obtained from the propagation delay of a signal going through a communication medium. However, in wireless networks, this propagation delay is very small (order of micro-seconds). Due to this fact, parallel simulation techniques have not been noticeable, and sometimes it is even worse than a sequential simulation. For that, there have been several research efforts to improve the speed performance of sequential wireless simulation and to enhance scalability of the existing simulation environments [16][17].

Many works have been proposed in which are evaluated different performance metrics which measure different features of the communication protocols. In [18] the authors evaluated three well-known routing protocols varying the number of nodes. However, they also follow some of the detected bad practices. For instance they do not address the propagation model, they do not depict the confidence intervals, the source and destination pairs are not selected and unexpected results also appear in the simulation results. One of detected problems in previous research work was the use of unrealistic traffic patterns, the most common one is the use of CBR. In [19] is used FTP and TELNET as traffic pattern and it is also studied the behaviour of three different routing protocols. The authors concluded that AODV shows the best performance for FTP and TELNET. In order to evaluate the behaviour of the routing protocols when the congestion of the network increases, in [20] the authors proposed vary the number of source and destination nodes but they followed one of the detected bad practices, the selection is done randomly, among others. Such as: random waypoint mobility model is used as mobility model or the propagation model is not showed. In this study, they concluded that the best performance results are achieved under low traffic load and depending on the measured performance metric, the best routing protocol will be different.

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5. AN EVALUATION METHODOLOGY FOR RELIABLE SIMULATION BASED STUDIES OF ROUTING PROTOCOLS IN VANETS

This chapter provides a methodology to improve the measurement of routing protocols performance in VANET urban scenarios. Section 5.1 describes the proposed methodology to solve the detected problems by researchers in previous works; it includes many simulation aspects such as Warm Up period, selection of communication pairs, number of simulations, mobility models, performance metrics and simulation analyses. The proposed methodology is validated by the comparison of the performance of several well-known reactive routing protocols such as AODV [1], LAR [2] and DYMO [3] with and without using the proposed methodology. The results are shown in the last section of this chapter.

5.1. The proposed methodology for reliable simulations in VANETs

Figure 9 shows a block diagram containing the main points of the proposed methodology such as the communication pair selection, the measurement period, the selection of number of simulations, the selection of a mobility model, the performance metrics and the analyses. The main objectives of the proposed methodology are, i) to highlight relevant simulation parameters that affect the simulation results, and ii) to provide a set of guidelines on the selection of these simulation parameters to reduce the dispersion of results and to obtain more reliable statistics. In the next subsection, we describe in more detail each point of the proposed methodology.

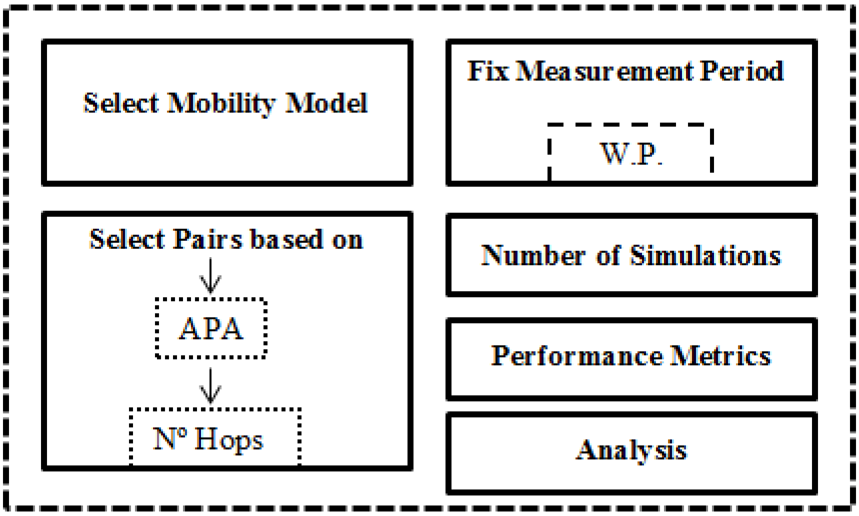

Figure 9 Main aspects of the proposed methodology

5.1.1. Measurement period

The measurement period is an important concept to carry out good simulations for VANETs. The *Warm Up period* (W.P. in Figure 10) is the time frame which ensures the stability of three relevant simulation aspects such as: i) all communication pairs have started transmitting application packets. ii) The mobility model has achieved a stable state. iii) The buffers of the nodes have stabilized.

Notice that the establishment of communications among a source-destination pairs can start at different times. Normally the starting times are selected randomly, so some pairs could have more time to transmit data packets than others. This fact can influence the simulation results if the selected pairs do not have the same properties in terms of average number of hops and path availability between the source and the destination nodes. By using a Warm Up period, we avoid discrepancies among the measurement period of the performance metrics during the simulation time. To obtain reliable and non-dispersed simulation results, performance metrics must be measured from W.P. value to the end of the simulation period, which is named as *Measurement Simulation Period* (M.S.P. in Figure 10). In order to select the Warm Up period, we have to consider two aspects, the first one is the period during which the communication flows are established, and the second aspect is the mobility model, since we need to guarantee that the mobility of nodes is stable.

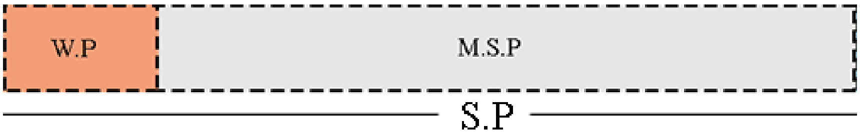

Figure 10 Status time bar

In order to show the importance of the Warm Up period values on the simulation results, we depict in Figure 11 the throughput performance metric, for different Warm up values for an urban scenario (4000x4000 m^2) corresponding to a fragment of the city of Washington D.C with 125 nodes moving with the IDM (Intelligent Driver Model) [4] mobility model. From now on we will refer to this scenario as the scenario under test that will be used to test several features of the proposed methodology. We use the throughput performance metric, which is defined as the number of application delivered packets in the simulation time. In the simulations, all source nodes start to generate application packets between 0 and 50s until the end of the simulation. The results shown in Figure 11 have been obtained using 25 different pairs selected randomly in the scenario under test. We include the 95% confidence intervals in Figure 11, from now on confidence intervals for the rest of figures shown in this chapter.

We can observe in Figure 11 that when the Warm Up value increases, the throughput also increases because the number of source nodes that have started to transmit application packets are higher. When the Warm Up value is higher than 50 (See 75 and 100 in Figure 11) the throughput values are very similar (See Table 10 for more details). Regarding the confidence intervals for each Warm Up value, they are high because the source and destination pairs are selected randomly. We highlight the importance of the communication pair selection in the next subsection. In consequence, the Warm Up value selection only affects the mean while the dispersion does not depend on this parameter (the dispersion is the descriptive statistic used by researchers in order to compare the performance of routing protocols). From now on we consider 50s as the Warm Up value recommended for the simulation of the scenario under test.

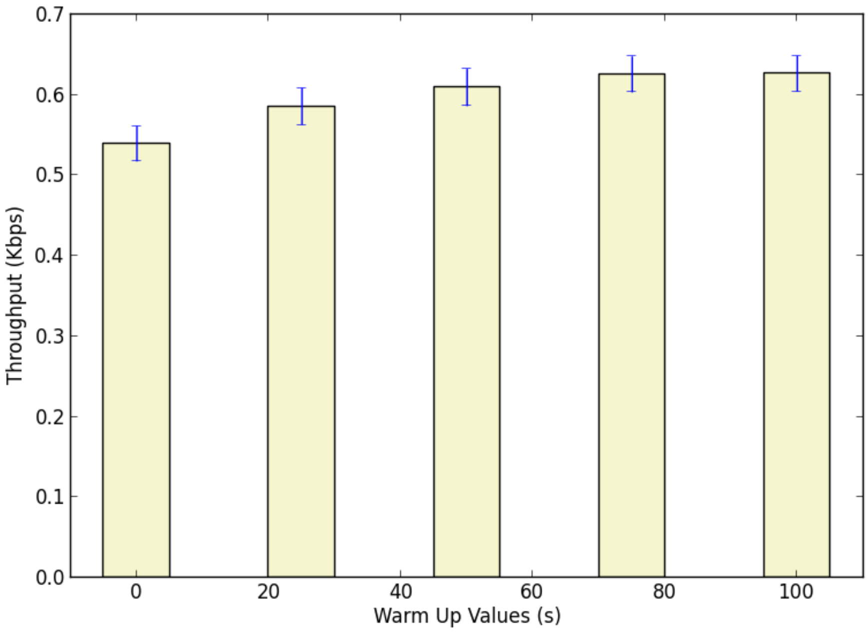

Figure 11 Throughput vs. Warm Up values

Warm up Values (s)	**0**	**25**	**50**	**75**	**100**
Throughput (Kbps)					
Mean	0.5395	0.5859	0.6093	0.6256	0.6265
Confidence interval	0.0220	0.0229	0.0231	0.0223	0.0222

Table 12 Throughput vs. Warm up values in the scenario under test

5.1.2. Source-destination selection

In this subsection, we present a communication pair selection based on four features that strongly affect the simulation results such as the path availability, the separation in number of hops between the source and destination nodes, and the repetition of source and destination nodes.

We define the communication pair selection as the mechanism by which the source and destination nodes of a communication flow are selected. The source node is responsible for generating the data packets, and the destination node is the target node in the network for those generated packets. Consequently, intermediate nodes will route the generated data packet towards the destination node using routing information. In simulation analyses, the communication pairs are normally selected at the beginning of the simulations. In most simulation-based studies of routing protocols for VANETs [5], the source and destination nodes are selected randomly among all nodes of the network. Although the original aim of this practice is achieving a fair selection of pairs, this can impact negatively on the dispersion of the obtained simulation results for several reasons. First, by using a random selection we cannot guarantee that all source-destination pairs have similar properties in terms of number of hops and path availability. Consequently, the simulation results may vary drastically from one pair to another. It is expected that routing protocols will obtain worse results when the number of hops increases and the path availability is lower. This situation is even more aggravated if the source-destination pair selected cannot be established. This means that it is not possible to establish a communication path from the source node to the destination node during the simulation time. Furthermore, the performance of the routing protocols can also be biased if the number of hops is very low. Second, outliers are prone to appear in simulation results when random selection is applied because of the great variability of the results. It affects to the mean of the simulation results. To solve this problem, we propose to use Average Path Availability (APA) [6] and the number of hops between the source and destination nodes as the key metrics to select source-destination pairs. APA is defined as the fraction of time during which a path is available between two nodes. We select source-destination pairs which have similar APA values because pairs with different APA values produce very dissimilar results. Figure 12 shows the distribution of APA values in the scenario under test. We can observe in Figure 12 that high values of APA are more probable than low values in the scenario under test but also that there are some APA values which are zero. This situation corresponds to source-destination pairs that cannot be established.

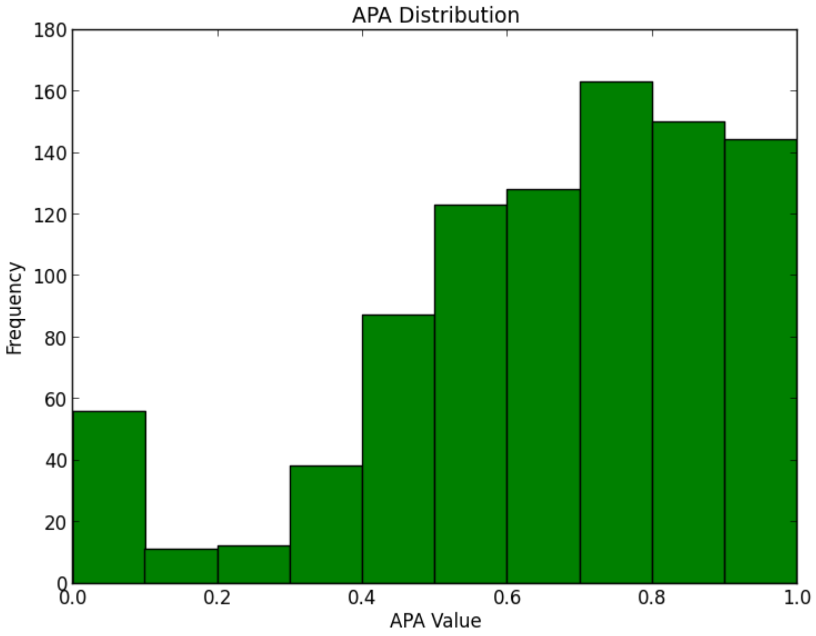

Figure 12 APA Distribution for the scenario under test

To highlight the impact of the APA value on the simulation results, we depict in Figure 13 the throughput for different APA values in the scenario under test. We can observe in Figure 13 that when the APA value increases, the throughput also increases (See Table 13 for more details). The reason is that the available communication paths between the source and destination nodes are higher. We also depict in Figure 13 the confidence intervals of the measurements (blue vertical line in Figure 13) for each obtained throughput value. The confidence intervals are considerably lower for higher values of APA. Notice that if we select source and destination pairs randomly we could pick pairs with different APA values and, in consequence, the simulation results will be more disperse. Let us illustrate this situation with an example, if we select randomly two communication pairs with very different APA values such as 0.2 and 1.0, we will obtain 0.20 Kbps and 0.86 Kbps respectively for the throughput (See Table 13 for more details). The mean of both throughput values will be 0.53 Kbps, and the confidence interval 0.65, which is quite high related to the obtained mean. Consequently, the obtained mean does not reflect the performance of AODV in the scenario under test. The reason is that two different APA values represent two different network conditions from the source node viewpoint. Conversely, if we select the communication pairs with similar APA values, we will guarantee that the network conditions in terms of connectivity will not change from one communication pair to another. As a result, we will achieve less disperse results.

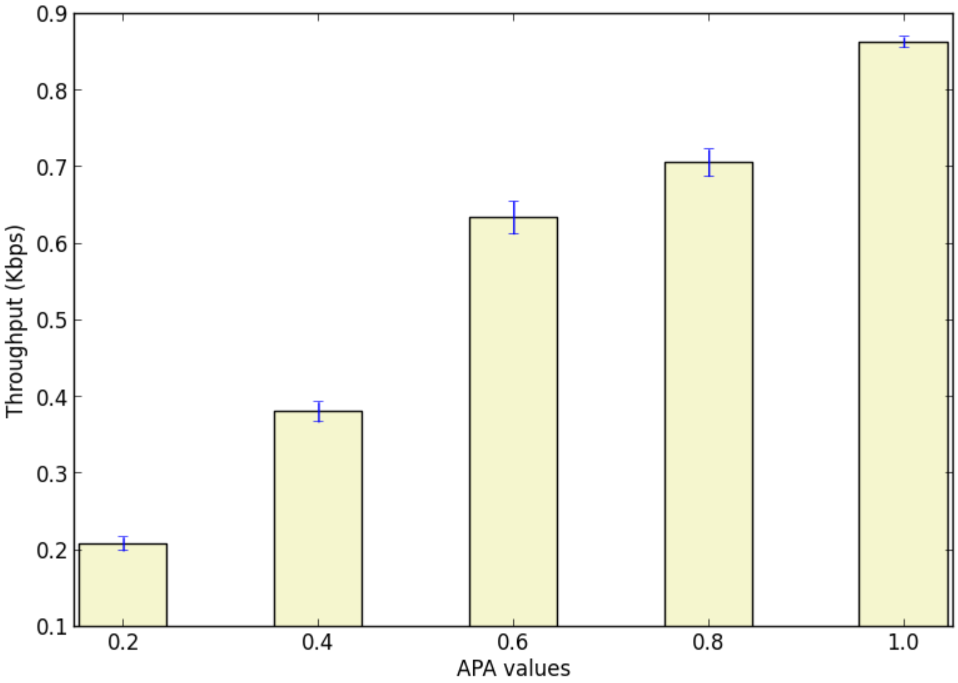

Figure 13 Throughput vs. APA values

APA value	0.2	0.4	0.6	0.8	1
Throughput (Kbps)					
Mean	0.2076	0.3799	0.6337	0.7051	0.8625
Confidence interval	0.0091	0 .0132	0.0216	0.0178	0.0070

Table 13 Throughput vs. APA values in the scenario under test

Once introduced the importance of the APA value in the simulation results, the next step in the proposed communication pair selection is to present a mechanism to choose a number of pairs that have similar values of APA. It is not a trivial task because in general the APA value depends on the topological characteristics of the simulation scenario such as the density and mobility of nodes. In particular, the density of nodes plays an important role. As a rule, the higher the density of nodes, the higher the APA value on average in the network. Consequently, the selection will be different according to the density of nodes in the network. As a primary condition, we should guarantee that there are a significant number of source-destination pairs in the network which can be selected as a valid pairs. For this reason we have to fix a value of APA for each density of nodes which assures this condition, target APA from now on. We represent the inverse of the cumulative distribution function (1-CDF) for the APA values in the aforementioned simulation scenario in Figure 14, but in this case, varying the number of nodes in the network in order to obtain different values of density. Notice that 1-CDF describes the probability that the APA value (considered as a random variable) is higher or equal than a given value. It is obvious that the most restrictive case is for the lowest density level (50 nodes) in which the APA values are in general very low. We state that the 1-CDF value of the target APA for a given scenario should be at least 20 % in order to have enough number of source-destination pairs to be selected. This condition is marked in Figure 14 with black points.

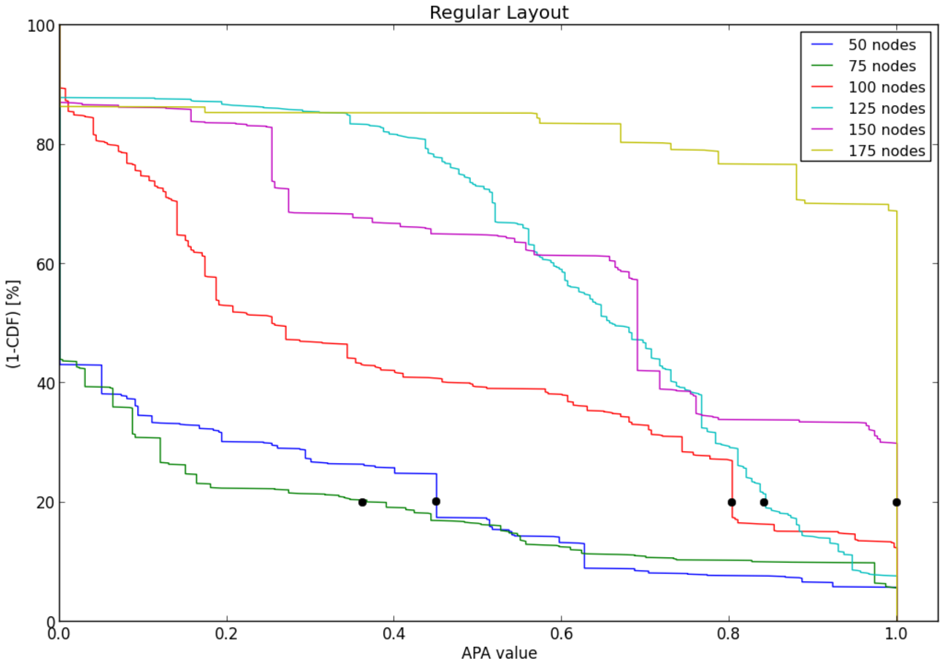

Figure 14 Inverse cumulative distribution function of the APA for different density levels

Scenario	Target APA
50 nodes	0.370
75 nodes	0.452
100 nodes	0.811
125 nodes	0.846
150 nodes	1.0
175 nodes	1.0

Table 14 Target APA values

Following the above described APA condition, Table 14 contains the minimum target

APA values that accomplish such condition for each density level.

The next step in the communication pairs' selection is to select those that are separated by the same number of hops on average. Notice that the APA value provides an idea about the availability of a communication path between the source node and the destination node, but it does not take into account the separation in terms of the number of hops in the scenario under test (See Figure 15).

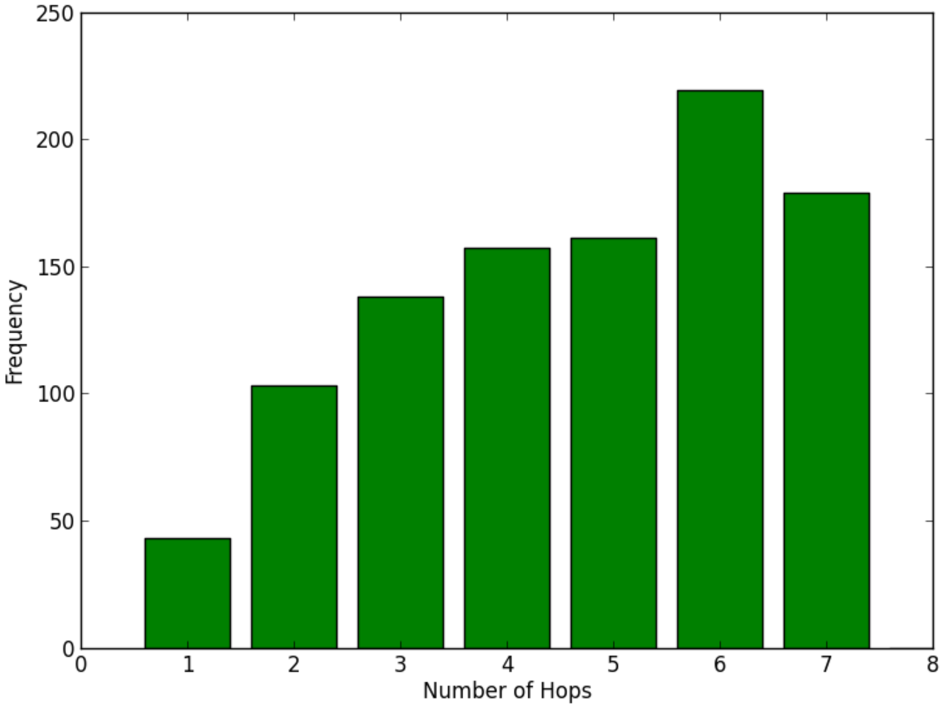

Figure 15 Number of hops distribution for the scenario under test

The minimum number of hops to reach a destination node is 1, this situation corresponds to the situation in which the destination node is within the source node coverage, and the maximum number of hops is 7. To ensure a reliable and fair evaluation of the routing protocols, we should fix a similar number of hops for each selected communication pair since the number of hops impacts significantly in the obtained simulation results as shown in Figure 16. Figure 16 shows that the throughput of the network is reduced (See Table 15 for more details) as the number of hops in the selected communication pairs increases. In order to illustrate the importance of the separation in number of hops, we use another well-known performance metric such as the NRL (Normalized Routing Load) (red line in Figure 8). This metric is defined as the ratio between routing packets and the total number of delivered application packets. In Figure 16 the NRL increases (See Table 15 for more details) as the number of hops increases because the routing protocol needs to generate a larger number of control packets to discover/maintain the routes. This metric is directly related to the energy consumption [7]. The confidence intervals for both metrics also increase (blue and red vertical lines in Figure 16 respectively) as the number of hops between source and destination nodes increase. If we select source and destination pairs randomly, we could pick pairs separated by very different hop number. Consequently, the simulation results will be more disperse. Let us consider an example of this situation in which we focus on the NRL metric. If we select randomly two pairs separated by very different number of hops such as 2 and 7, the NRL values obtained for these values are 1.24 and 9.96 respectively (See Table 15 for more details). The mean of both values will be 5.6 and the confidence interval 8.54. Notice that the obtained confidence interval is too high compared with the mean. Consequently, the obtained mean does not reflect the performance of AODV in the scenario under test.

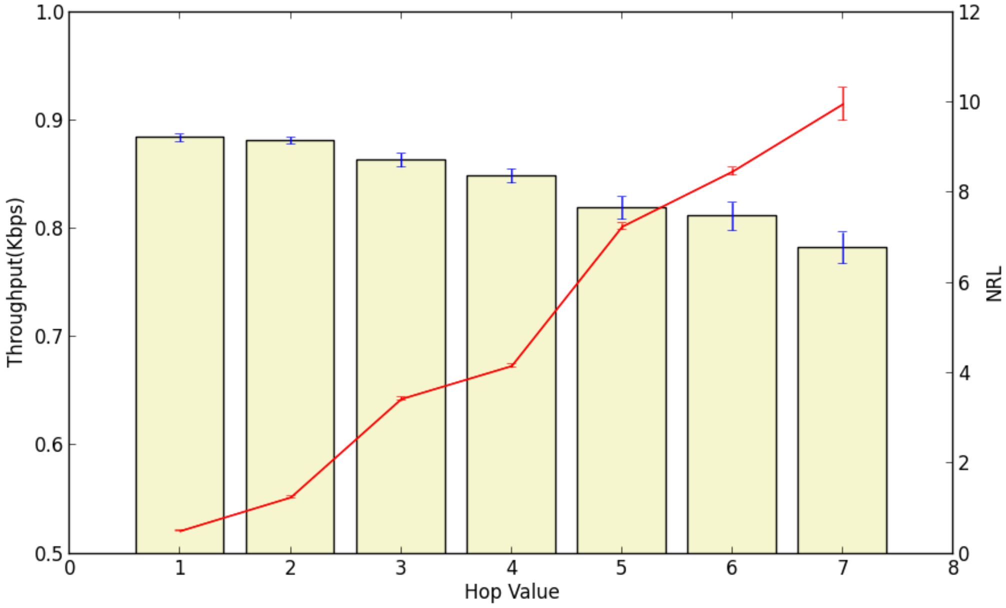

Figure 16 Throughput and NRL vs number of hops in the scenario under test

Number of hops	1	2	3	4	5	6	7
Throughput (Kbps)							
Mean	0.8835	0.8812	0.8629	0.8484	0.8189	0.8111	0.7820
Confidence	0.003			0.0066		0.0128	0.014

interval	3	0.0031	0.0063		0.0104		3
NRL							
Mean	0.5006	1.2448	3.4239	4.1562	7.2428	8.4652	9.9593
Confidence interval	0.0169	0.0251	0.0449	0.0390	0.0704	0.0858	0.3664

Table 15 Statistics measures for Throughput vs number of hops

Following the same procedure for the APA selection, we need a selection mechanism to choose communication pairs with similar separation in terms of the number of hops. Again, we use the inverse cumulative distribution (1-CDF) for different density levels in order to get more insight into the distribution of the number of hops. The obtained results are shown in Figure 17.

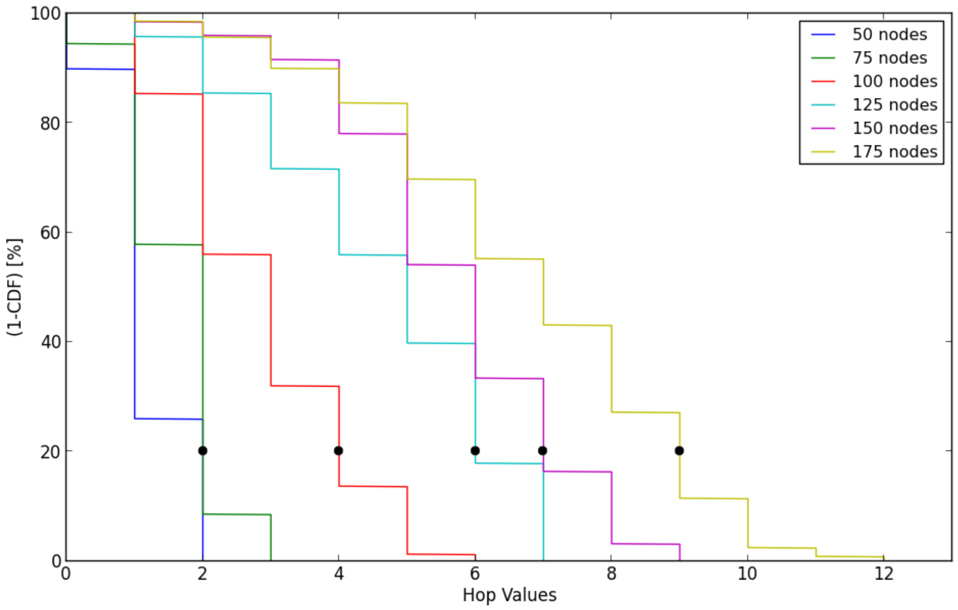

Figure 17 Inverse cumulative distribution function of the number of hops for different density levels

In this case, we should select the highest possible number of hops since we are interested in evaluating the performance of routing protocols, but also we must ensure that there are enough source destination pairs. For this reason, we should focus on the most restrictive case, which corresponds to a density level of 50 nodes, as it is very difficult to select communication pairs that are separated by more than 2 hops (See Figure 17). As with the APA value, we state that the 1-CDF value of the target number of hops for a given scenario should be at least 20 % in order to have enough number of source-destination pairs. This condition is marked in Figure 17 with black points. Table 16 shows the target number of hops values that accomplish a minimum number of pairs with that condition in the scenario under test. From here on, when we refer to the proposed methodology we must ensure that the two above conditions (APA and number of hops) are fulfilled.

Scenario	Target Hops
50 nodes	2
75 nodes	2
100 nodes	4
125 nodes	6
150 nodes	7
175 nodes	9

Table 16 Target hops values

Another important feature that should be controlled in the selection of communication pairs is the possibility of several communication pairs having the same source and destination nodes. Although the actual source and destination nodes will depend on the underlying application in the VANET, for a reliable evaluation we should guarantee that the selected pairs have similar properties in terms of repetitions of source and/or destination nodes. A great variability in the repetition of selected nodes can impact significantly on the simulation results. For instance, if destination nodes are very frequently repeated then the queue of these nodes can saturate, and this fact can cause dropped packets.

To highlight the importance of the repetition of the source and destination nodes, we depict in Figure 18 and Figure 19 the throughput for different numbers of repeated source and destination nodes in the scenario under test.

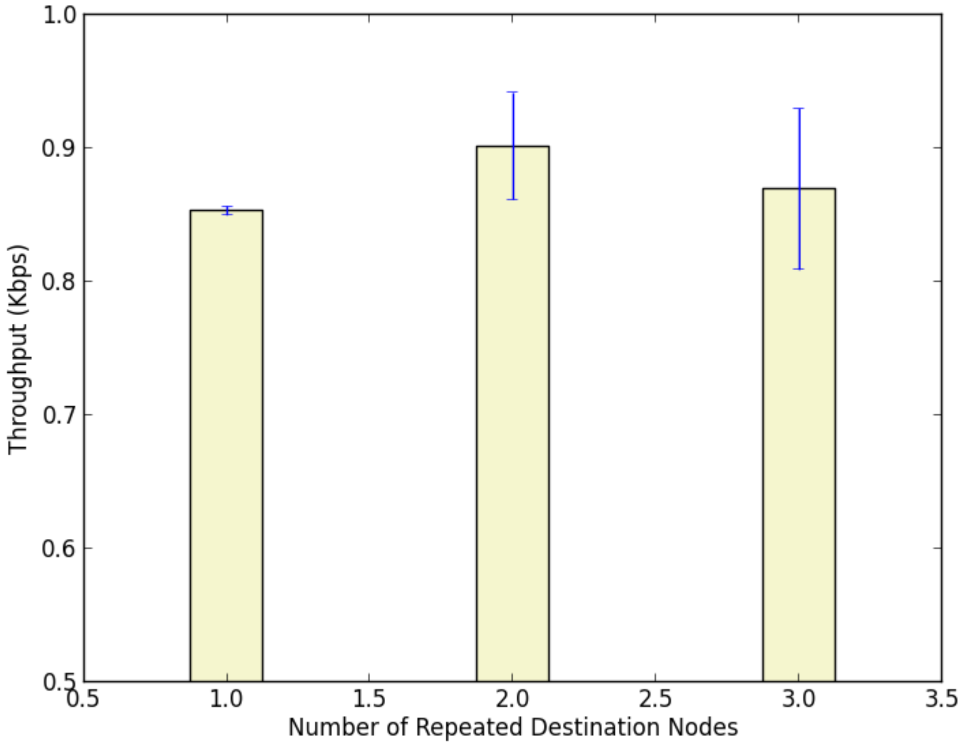

Figure 18 Throughput vs repeated destination nodes

Number of Repeated Destination Nodes	**1**	**2**	**3**
Throughput (Kbps)			
Mean	0.8529	0.9012	0.8690
Confidence interval	0.0034	0.0399	0.0504

Table 17 Throughput vs repeated destination nodes values in the scenario under test

As we can see in Figure 18, when the number of repeated destination nodes increases the confidence intervals are higher (See Table 17 for more details) because the number of application packets lost in the destination node buffers are higher.

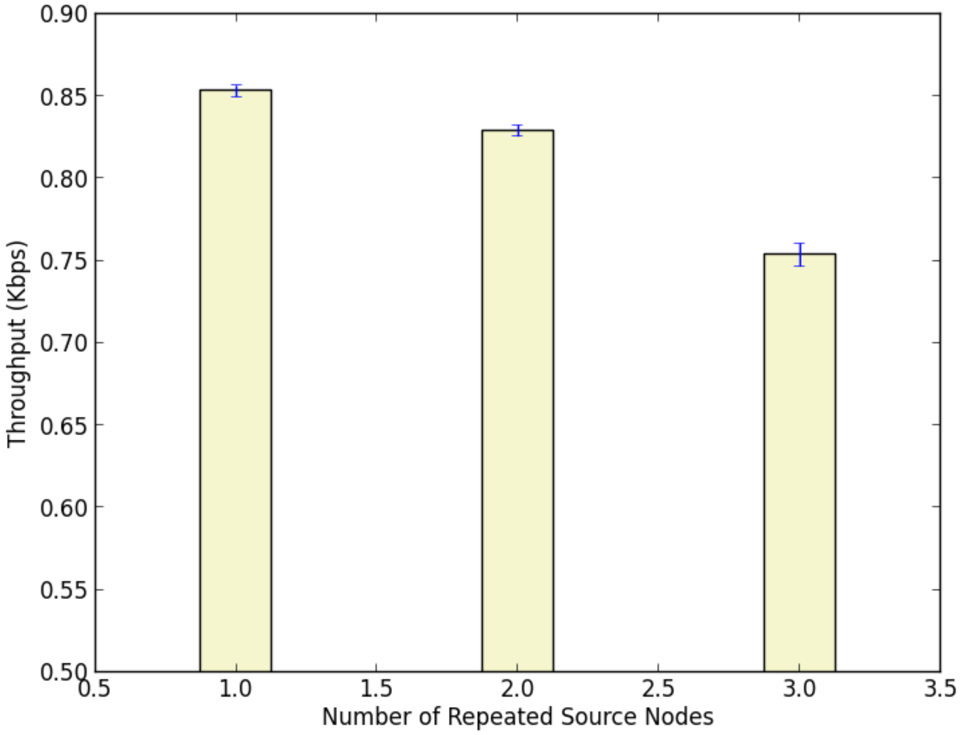

Figure 19 Throughput vs repeated source nodes

Number of Repeated Source Pairs	1	2	3
Throughput (Kbps)			
Mean	0.8529	0.8289	0.7535
Confidence interval	0.0034	0.0035	0.0070

Table 18 Throughput vs repeated source nodes values in the scenario under test

We can observe in Figure 19 that as the number of repeated source nodes increase the results are more disperse (See Table 18 for more details) because there are some application packets lost in the intermediate node buffers due to traffic congestion. However, the results are lesser scattered than in the case of repeated destination nodes (See figure Figure 18). This is due to the fact that besides the intermediate node buffers, the destination nodes buffers are even more congested causing more collisions and contention in the shared wireless medium.

When random selection of communication pairs is used, we cannot control whether the destination and source nodes are repeated or not. Such repetition does not mean that the simulated scenario is unrealistic. However, this situation can favor the performance of a routing protocol with respect to others. For example in the case that one routing protocol is specifically designed to take into account this network condition. Applying the proposed selection, we can guarantee that all routing protocols are evaluated under the same network conditions.

Finally, to illustrate the importance of the APA, the number of hops, the Warm Up period, and the repetition of source/destination nodes, we compare the simulation results in the scenario under test with and without considering the aforementioned simulation practices. Table 19 details the nomenclature that will be used to describe the following simulation results.

Acronym	**Meaning**
R.P.	Randomly selected pairs
R.P with M.P.	Randomly selected pairs with measurement period
S.P.	Selected pairs based on APA and number of hops
S.P with M.P.	S.P with measurement period
S.R.	Randomly selected pairs with repeated source
D.R.	Randomly selected pairs with repeated destination
S.R. with M.P. + S.P.	Repeated source nodes selected based on target APA and number of hops with measurement period
D.R. with M.P. +S.P.	Repeated destination nodes selected based on APA and number of hops with measurement period

Table 19 Chosen nomenclature

Figure 20 shows the throughput obtained in the scenario under test with 25 different source-destination pairs. We depict these results with boxplot graphs and we also highlight with a green point the obtained mean of the samples. The boxplot graphs are used to better understand how values are spaced out in different sets of data. The bottom line of the box represents the first quartile (Q1), the top line represents the third quartile (Q3) and the distance between them is the interquartile range *(IQR=Q3-Q1*). Another important aspect in the boxplot graphs are the whiskers which depend on the IQR. The upper whisker is determined by the equation *Q3 + 1.5*(IQR)* while the bottom value is determined by *Q1 – 1.5*(IQR).* Therefore if we have a set of data bits scattered, the IQR and the whiskers will be low. In this work, we will focus on the IQR to measure the level of dispersion. Figure 20 includes results for *R.P.*, *R.P. with M.P.*, *S.P.* and *S.P. with M.P.* cases (See Table 8 for more details).

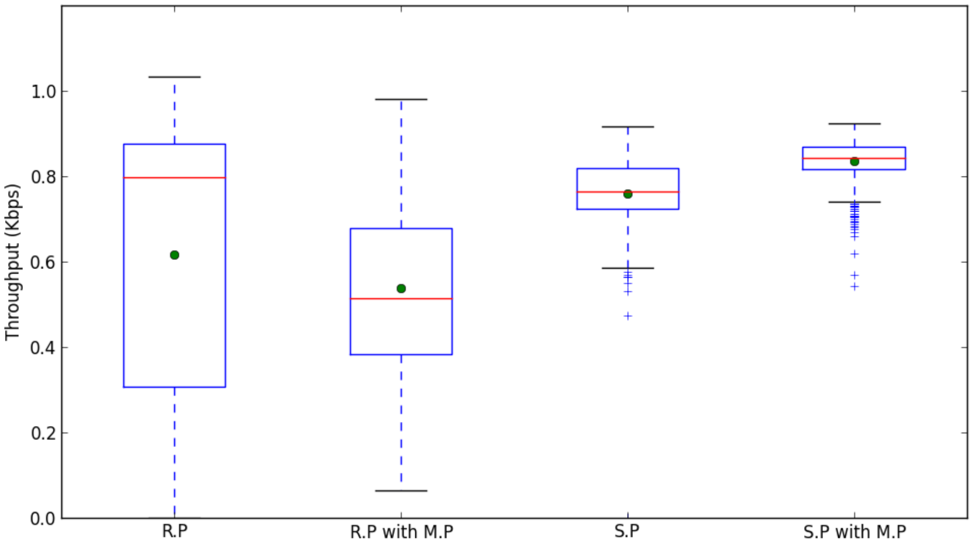

Figure 20 Throughput vs source destination pair selection

Using the Warm Up period (See *R.P with M.P* in Figure 20) we can observe in Figure 20 that the distance between first and third percentile is smaller than without these periods (*R.P* in Figure 20). This means that we have less scattered measures. To highlight the importance of Warm Up period we focus on the selected pairs based on APA and number of hops case (S.P in Figure 20). We can observe that in this case the IQR is lower than in the case of not using the selection technique (See *R.P and R.P with M.P* in Figure 20) because the set of values is lesser scattered. If we also use the measurement period (S*.P with M.P* in Figure 20) the IQR is lesser. Consequently, we are able to obtain more reliable simulation results by using the proposed methodology.

Figure 21 shows the simulation results for *S.R*, *D.R*, *S.R with M.P + S.P* and *D.R with M.P + S.P* cases. Again, the simulation scenario is the scenario under test with 25 communication pairs, and the maximum number of repetitions for both the source and destination nodes is 3. It means that nodes can be selected as a source or destination in 3 communication pairs. According to the results shown in Figure 21, the repetition of source nodes affects more significantly the simulation results than the repetition of the destination nodes. Additionally, including the proposed selection based on APA and the number of hops, the simulation results are even better in terms of dispersion.

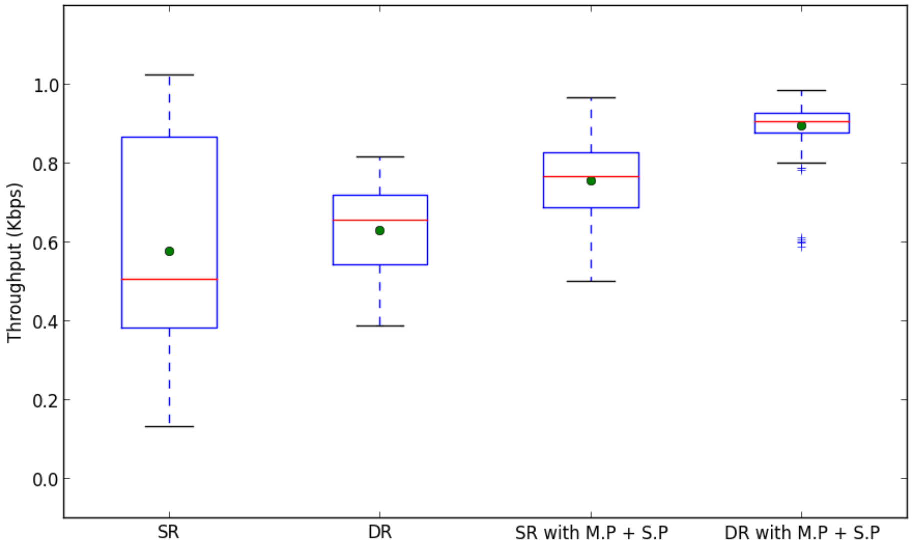

Figure 21 Throughput vs source destination pair selection

5.1.3. Number of simulations

Another important aspect to be considered when conducting simulation-based studies is the number of simulations that should be carried out for each data point in the results. Clearly, the more simulation trials, the more representative data sample we obtain, however, the simulation results also incur in computing time consumption. Consequently, a trade-off between the number of simulations and the computing time should be reached. We should not devote more time than the necessary to conduct simulations. Thus, the number of simulations should be selected in order to obtain a representative data sample without requiring excessive simulation time. Figure 22 shows the throughput results and the required computing time for different number of traffic seeds (number of simulations). The chosen simulation scenario is the same one described in the previous section (the scenario under test) with 25 source-destination pairs of communications. As expected, we can observe that the computing time is higher as the number of seeds increases as well (See Table 20 for more details). When we use the proposed pair selection and the measurement period, the computing time is lower than when we do not use them. The main reason is that the network is less congested because the number of routing packets is lower, due to the APA based selection. Since we aim to obtain reliable simulation results, we want a good confidence interval, which includes non-dispersed results with the lowest computing time. Figure 22 shows two different cases, the first one corresponds to the proposed communication pair selection and the second one is for the case of using random pairs.

The obtained results are not similar in terms of the obtained average mean. Using the proposed methodology we obtain better results than non using it (See Table 20 for more details). In addition, the proposed communication pairs selection needs a lower number of simulations to obtain better and lesser disperse results, as shown by the lower confidence intervals. To highlight the importance of our methodology in term of computing time consumption, we focus on the 5 seed case in which we achieve a very good confidence interval without requiring excessive simulation time. We define a new metric to evaluate this situation, the ratio between the confidence interval and the mean. From now on we will name it as *normalized confidence interval*. If we use the proposed measurement period and the communication pair selection mechanism, the *normalized confidence interval* takes the value of 0.01 for 5 seeds. The number of simulations to reach this value without the measurement period and the proposed communication n pair selection mechanism is 80 simulations. It means that we need 16 times more simulations to obtain the same dispersion. In terms of computing time, we save 279.3 s (287.9 s – 8.6 s) when using the proposed methodology.

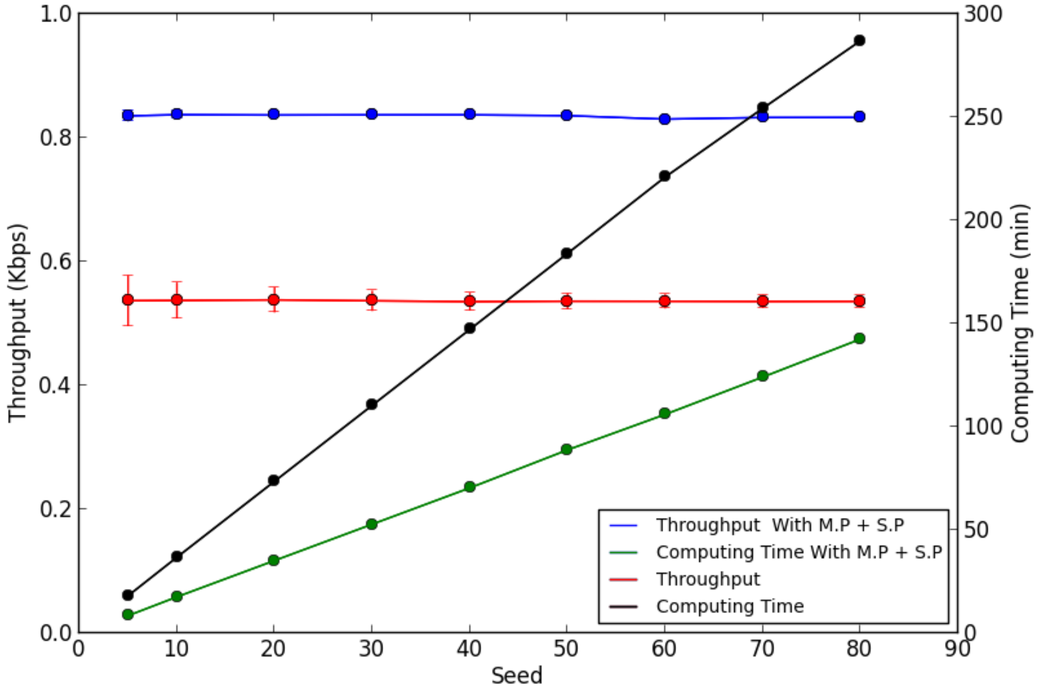

Figure 22 Throughput and computing time vs number of simulations

Number of simulations (seeds)	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**

Thoughput (Kbps)									
With M.P + S.P									
Mean	0.8353	0.8372	0.8367	0.8369	0.8370	0.8358	0.8301	0.8327	0.8328
Confidence interval	0.0089	0.0061	0.0043	0.0041	0.0034	0.0030	0.0027	0.0026	0.0025
Computing Time (min)	8.6	17.6	35.2	52.8	70.4	88.8	106	124.1	142.3
Without M.P + S.P									
Mean	0.5369	0.5374	0.5381	0.5368	0.5354	0.5362	0.5360	0.5365	0.5370
Confidence interval	0.0411	0.0291	0.0203	0.0165	0.0143	0.0127	0.0115	0.0109	0.0089
Computing Time (min)	16.5	36.8	73.6	110.4	147.2	184.0	221.0	254.3	287.9

Table 20 Statistics measures for Throughput vs number of simulations

5.1.4. Mobility in VANETs

A critical issue in VANETs simulation studies is the need for a mobility model that reflects the real behaviour of vehicular traffic in urban scenarios.

The next objective of the proposed methodology is to determine how to select a representative VANET scenario to evaluate routing protocols. According to the classification made in [8], the cities can be categorized using the density of streets and junctions as simple, regular and complex layouts. Three cities that fall in such classification are Los Angeles, Washington and Tokyo respectively. We have studied the APA and the number of hops values found in these three layouts.

Figure 23 shows the distribution of the APA and the number of hops for each layout. We can observe that in general the number of hops is higher for more complex layouts. Regarding the APA distribution, we observe similar distributions for regular and complex layouts, where APA values higher than 0.5 are more probable.

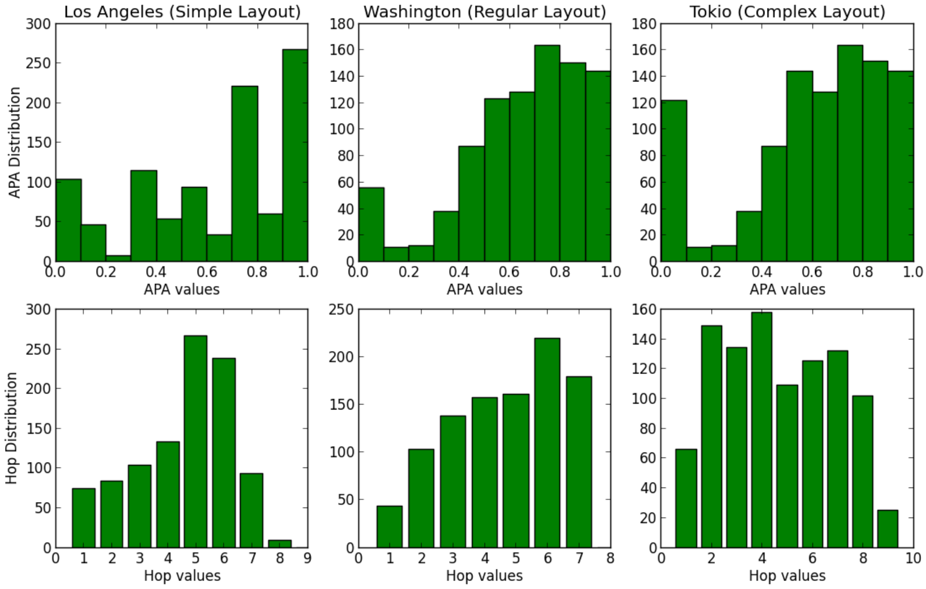

Figure 23 APA and number of hops distribution for different layout

Moreover and regardless of the layout, we can select APA values within [0, 1] interval according to Figure 23. Similarly, for the three layouts we can select pairs separated by the same or similar number of hops. Consequently, controlling the APA and separation in number of hops between the source and destination nodes, we can expect similar simulation results for the three layouts as long as we apply the proposed methodology. This fact is shown in Figure 24, which represents the simulation results obtained by the proposed methodology (With P.M in Figure 24) (See Table 10 for more details) and the simulation results without using the proposed methodology (Without P.M in Figure 24). When the proposed methodology is applied, the results are less disperse and very similar to each other.

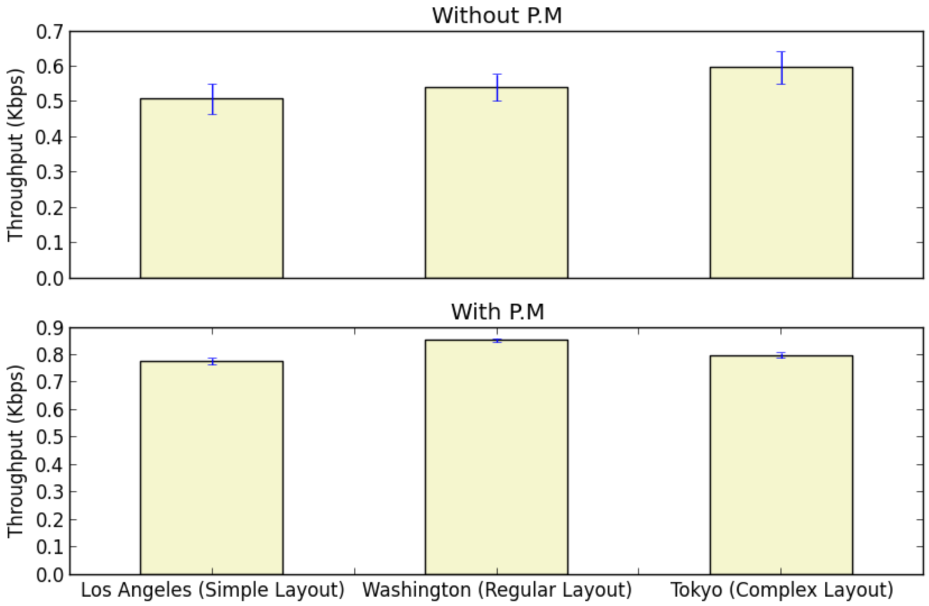

Figure 24 Throughput vs roadmap profile classification

Layout Profile	**Los Angeles(Simple)**	**Washington (Regular)**	**Tokyo (Complex)**
Without P.M.			
Mean	0.5073	0.5394	0.5958
C.I.	0.0428	0.0374	0.0450
With P.M.			
Mean	0.7754	0.8527	0.7967
C.I.	0.0113	0.0063	0.0093

Table 21 Statistics measures for Throughput vs layout classification

Next step is to study the inverse of the cumulative distribution function for the APA values. In Figure 25, we can observe that we obtain similar results for the three layouts. It means that for the same APA, the connectivity of the network is very similar and does not depend on the layout. This might be explained by fact that the simulations do not consider obstacles like buildings or other vehicles.

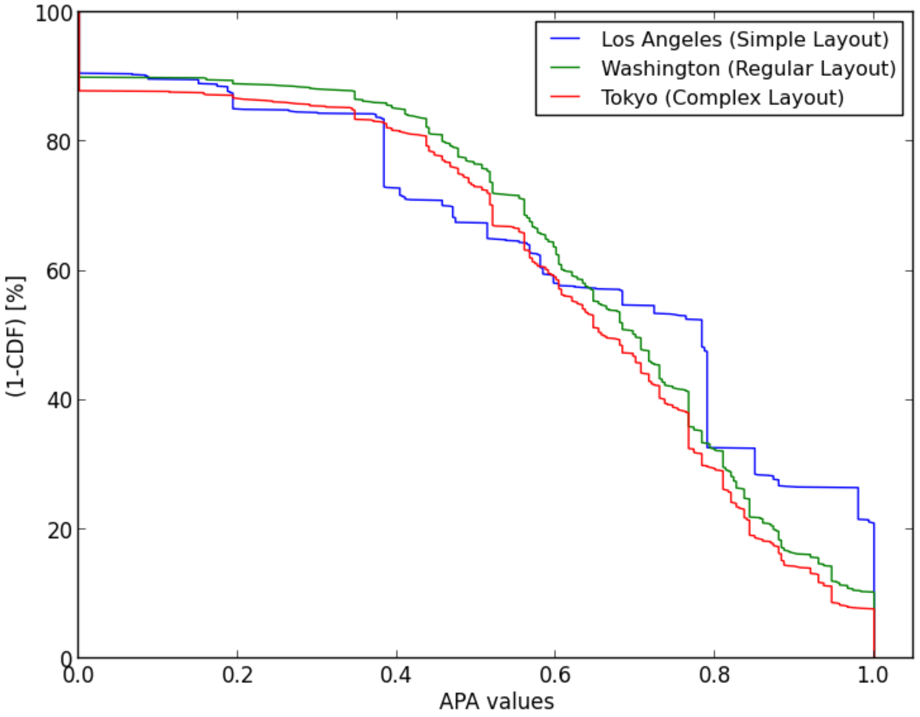

Figure 25 1-CDF for APA distribution for the three considered layouts

The last step in this analysis of the mobility of nodes is to study the cumulative distribution function (1-CDF) for the separation of nodes in terms of the number of hops. As we can observe in Figure 26, the results for the three layouts are very similar. However, for the Complex layout case the maximum number of hops is higher than for the other layouts. From now on in this study, we will use a city with a regular layout such as Washington because it has an intermediate behaviour in terms of the APA and number of hops distribution.

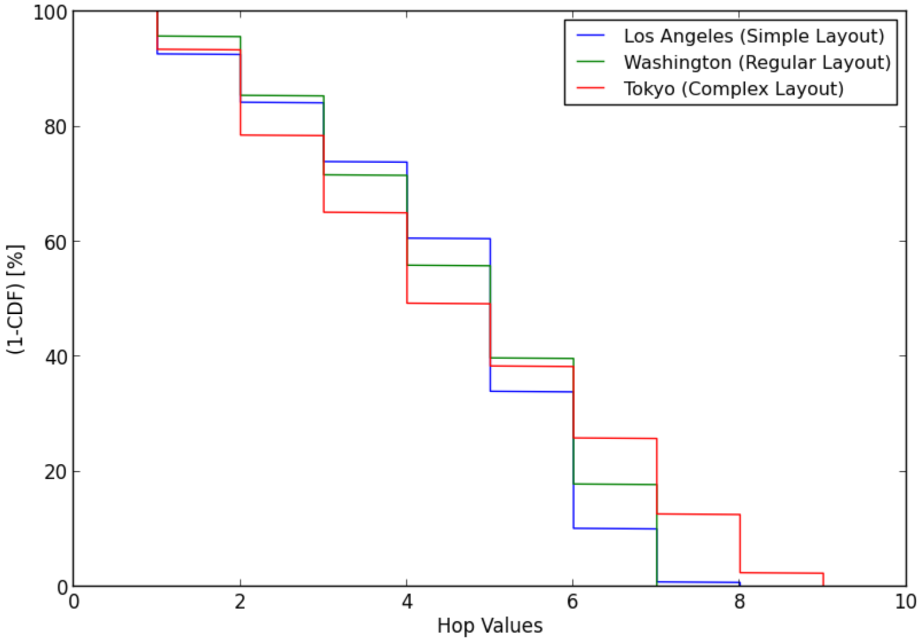

Figure 26 1-CDF for the number of hops separation for the three considered layouts

Figure 27 depicts the area of Washington that will be used in the simulation results section. The left-hand part of Figure 27 shows a real capture of the area used in our simulations, the right-hand part shows the model obtained from C4R and the bottom part depicts the movements of the vehicles over the selected area, with each color representing a different node.

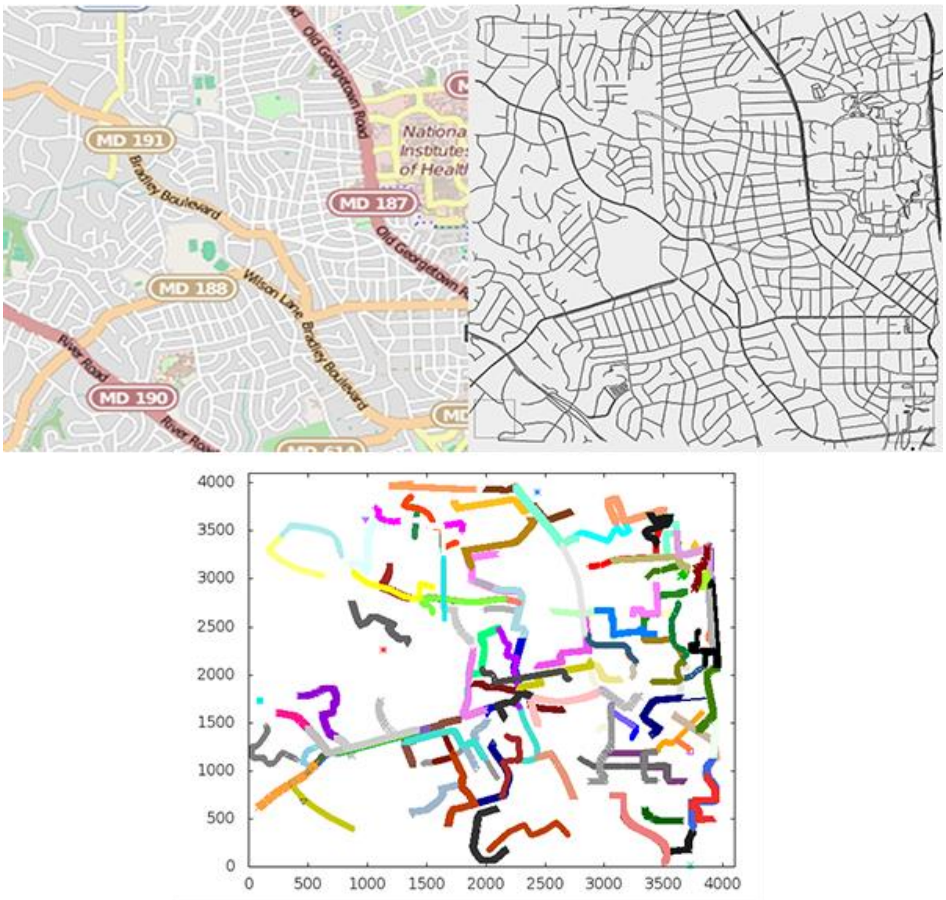

Figure 27 Washington layout and node movements in the scenario under test with 125 nodes

To model the behaviour of the drivers we use the IDM model [4]. The chosen values for each parameter are those that ensure a maximum speed of 30Km/h, which is the speed limit in urban environments. We also ensure a minimum security distance between two vehicles trying to model the real driving conditions in urban scenarios. In this case we are simulating a normal driving behaviour as described in [4] with a minimum security distance of 2 meters.

5.1.5. Performance metrics

Another important aspect to be considered when evaluating routing protocols is which performance metrics should be used in order to represent an unbiased performance of the routing protocols. It is important to use metrics that exhibit the performance of the routing protocols in different conditions. The following performance metrics are some of the most used in simulation-based studies:

Throughput (THR): It is the sum of the data packets in the simulation period.

$$THR\ (Kbps) = \frac{\sum Delivered\ Application\ Packets}{Simulation\ time}$$

(4)

Average End-to-End Delay (*E2E*): It is defined as the time taken for a data packet to be transmitted across an ad hoc network from the source to the destination node.

$$E2E\ (s) = \frac{\sum(Delivered\ Time - Transmitted\ Time)}{Number\ of\ packets\ succesfully\ delivered}$$

(5)

Normalized Routing Load (*NRL*): It is the ratio of the total routing packets to the total delivered data packets.

$$NRL\ = \frac{\sum \text{Routing}\ Packets}{\sum Delivered\ Application\ Packets}$$

(6)

Packet Delivery Fraction (PDF): It is the ratio of the number of packets delivered to the receiver, to the number of packets sent by the source.

$$PDF\ (Kbps) = \frac{\sum Delivered\ Application\ Packets}{\sum Sent\ Packets}$$

(7)

Jitter (*JIT*): It is the delay between two consecutive packet deliveries at a node.

$$JIT\ = \frac{\sum delays_{packet\ delivered}}{Packet_{Application_{delivered}}}$$

(8)

Additionally, in this research we propose a new performance metric, the Route Activity

Time (RAT), which is aimed at evaluating the capability of a routing protocol to maintain an active route between the source and the destination nodes. The formal definition of RAT is as follows:

Route Activity Time (*RAT*): It is the period of time during which a communication path is available between the source and the destination nodes. In routing protocols based on request, reply and error messages, such as AODV, DSR, and DYMO, it is the period elapsed between the time at which the reply message arrives at the source node and the time at which an error message of such route is generated.

$$RAT(s) \ = \mathrm{Error}_{\mathrm{time}} - Reply_{time} \qquad (9)$$

Notice that the RAT metric measures how the routing protocols manage the path availability. In theory, we control the APA values selecting the communication pairs, however, the real time in which a communication path is established between a source and a destination node will depend on the underlying routing protocol and the network conditions.

Figure 23 summarizes the desirable values for each metric used to evaluate the routing protocols performance.

Metric	**THR**	**E2E**	**NRL**	**PDF**	**JIT**	**RAT**
Desirable values	*High*	*Low*	*Low*	*High*	*Low*	*High*

Table 22 Desirable values for the performance metrics

Although we have described six different performance metrics (4)-(8) to evaluate the performance of the routing protocols, we will only use four of them, THR(4), E2E(6), NRL(7) and RAT(9) in the next section, since the rest of them provide redundant information. By using the THR metric, we measure the performance of the routing protocols in terms of the number of delivered packets. With E2E we evaluate the average delay of the application packets. Using the proposed RAT metric, we measure how the routing protocols maintain the communication routes between the source and destination nodes. The NRL metric measures the number of routing packets used by the routing protocols and provides an idea about the power consumption of the routing protocol. Regarding PDF and JIT metrics, we do not use these metrics for the next reasons. First, the PDF metric also measures the number of delivery packets so this metric is similar to THR metric. Second, we do not use the JIT metric because it gives us an idea about the network delay and we are actually using E2E to measure this feature.

5.1.6. Simulation analyses

The objective at this point is to decide which analyses we should carried out for a good performance evaluation of routing protocols. In general, the number of nodes is a common parameter to vary in simulation-based studies in order to evaluate routing protocols under different density levels (connectivity). However, there are other parameters that also affect considerably the performance of routing protocols. For instance, the congestion is a common issue in multi-hop networks because nodes should share the wireless medium, and consequently, routing and application packets should compete for the wireless medium. The congestion in the network can be modified by varying some parameters of the communication flows between the source and destination nodes such as data rate, size of packets, and number of flows. Among the mentioned parameters, we focus on the number of flows since we have proved the relevance to the selection of source-destination pairs. Therefore, we propose two different analyses. First, a density analysis based on varying the number of nodes for the same number of communication flows. Second, a congestion analysis, focused on varying the number of communication flows for the same number of nodes. With the first analysis, we evaluate the routing protocols under different connectivity levels and with low congestion conditions. In the second analysis, we set a medium-high value of density (high connectivity) and vary the congestion of the network to observe how well routing protocols perform under different levels of congestion.

To summarize the procedure described in this section, Table 23 provides the most important values of the proposed methodology and also the benefits of each of them.

Simulation parameter	**Selection**	**Benefit obtained**
S.P. = 300 s	**W. P.=** 50 s (**M.S.P.=**250 s)	Using W.P. we improve mean of the used performance metrics
Selection Pairs based On APA	Depending on the scenario and based on APA target	Applying the proposed methodology based on APA and Number of hops we reduce the dispersion.
Selection Pairs based On Hop Number	Depending on the scenario and based on number of hops target	

Performance Metrics	THR(4), E2E(6), NRL(7), RAT(9)	We can evaluate different features of the evaluated routing protocol.
Scenario	Washington (Regular layout)	We can emulate real scenarios.
Analysis	Congestion and density	We evaluate the routing protocols under different network conditions.

Table 23 Summary of the simulation parameters used in the proposed methodology

5.2. Evaluation of the proposed methodology

This section includes the results of the proposed methodology when evaluating routing protocols in VANETs. The aim is to show that the proposed methodology leads to more reliable simulation results. For this purpose, we compare the obtained results of several well-known and widely used routing protocols for multi-hop ad hoc networks such as AODV, LAR and DYMO with and without the proposed methodology.

5.2.1. Simulation environment settings

For the evaluation we use NS-2.34 [9] under a Debian Linux operating system. NS-2 is a simulation tool for replicating real life networking environments. To simulate urban mobility of vehicles, we use CityMob for Roadmaps (C4R) [9]. Table 24 summarizes the general simulation settings used. It is important to highlight some specific aspects of VANET simulations such as the MAC protocol used, which is the IEEE 802.11p [11]. This is based on the 802.11a standard and has the same structure. The main difference, compared to 802.11a, is its bandwidth, which is narrower in order to make the signal more resistant to fading and multipath propagation in the automotive environment. Another important difference is the operating frequency; in the case of 802.11p standard is 5.9 GHz, as opposed to the 802.11a, which is a standard operating at 5 GHz in Europe [12]. Regarding the propagation model, we use two-ray ground reflection model [13] because it gives more accurate prediction for long distances than the free space model. We select a transmission range of 500 m, which is a typical transmission range for VANET scenarios (the standard IEEE802.11p can reach up to 1000 m). The simulation time is 300 s, which is high enough to guarantee a good evaluation of routing protocols. The warm up period has been selected according the study conducted in previous section 5.1.1. The type of traffic is Constant Bit Rate (CBR), which is typically used in multi-hop scenarios with UDP transport layer. CBR traffic is suitable for real time applications. The transmission rate of application packets is 1 packet per second and the size of packet is 512 bytes. The simulation scenario is the one described in section 5.1.4. The maximum speed of nodes is 30 km/h. This maximum value is suitable for urban scenario, where the limited speed is about 50 km/h.

Parameter	**Value**
Simulation Time	300 s
Warm Up period	50 s
Routing Protocols	AODV,DYMO, LAR
Transmission range	500 m
MAC Protocol Type	IEEE802.11p
Number of Nodes	50, 75, 100, 125, 150, 175
Numbers of Sources	5, 10, 15, 20, 25
Traffic Types	CBR
Transport Layer	UDP
Maximum Packet in Queue	50
Packet Size	512 bytes
Packet Rate	1 packet/s
Area Size	4000*4000 m^2
Mobility model	Washington Layout
Propagation model	Two-ray ground
Maximum speed of nodes	30 km/h

Table 24 Simulation parameters

5.2.2. Simulation results

In this subsection we show the obtained results of the two different proposed analyses, the density analysis and the congestion analysis.

5.2.2.1. Density analysis

In this analysis we vary the number of nodes for the three used routing protocols, in steps of 25 each, within the interval [50, 175]. The number of communication flows is fixed to 5 (low congested scenario), the APA values are selected according to Table 3 and the maximum number of hops according to Table 5.

Figure 28, Figure 29 and Figure 30 show the simulation results for THR, RAT, E2E, NRL performance metrics, with their confidence intervals for each number of nodes. Figure

28, Figure 29 and Figure 30 include the results using the proposed methodology (Results with P.M in Figure 28, Figure 29 and Figure 30) and without using the proposed methodology (Results without P.M in Figure 28, Figure 29 and Figure 30). We depict the results for 5 and 30 simulations (seeds in Figure 28, Figure 29 and Figure 30) with and without applying the proposed methodology to check the differences between them in terms of the mean and the confidence interval. By using the proposed methodology, the results are in general, very similar in terms of mean. Nevertheless, the confidence intervals are lower for both numbers of simulations. But if we randomly select the source destination pairs, there are important differences in the mean values of some metrics and also in the confidence intervals which are large despite of using many simulations.

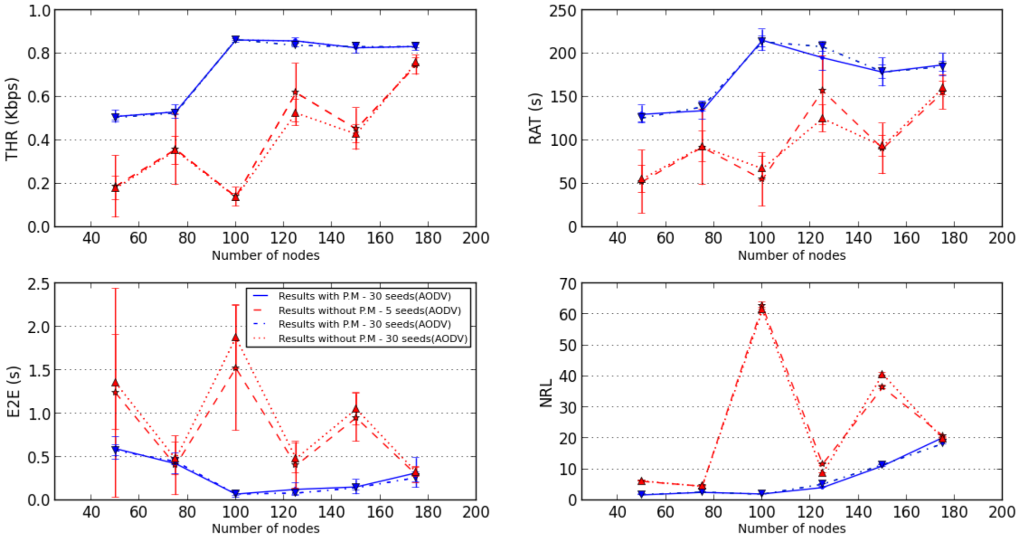

Figure 28 Results of the density analysis – AODV

Figure 28 clearly shows that the results obtained by AODV when using the proposed methodology are better and more reliable in terms of dispersion and tendency. Table 25 details the exact values of the mean and the confidence intervals of each performance metric for every number of nodes. We can observe that as the number of simulations increases the results are lesser scattered in both cases (With and Without P.M). However, the differences are small when applying the proposed methodology; it means that by using the proposed methodology we obtain good results, in terms of dispersion, with a low number of simulations. On the one hand, in the P.M case there are not important differences for all metrics, the results are similar. On the other hand, without P.M case there are differences in some of them, for instance RAT, E2E and NRL metrics.

Number of Nodes		**50**	**75**	**100**	**125**	**150**	**175**
AODV							
THR (Kbps)							
With P.M.							
5 seeds	Mean	0.5098	0.5310	0.8625	0.8582	0.8266	0.8325
	C.I.	0.0288	0.0328	0.0121	0.0119	0.0253	0.0184
30 seeds	Mean	0.5050	0.5262	0.8643	0.8377	0.8315	0.8317
	C.I.	0.0126	0.0112	0.0041	0.0077	0.0078	0.0080
Without P.M.							
5 seeds	Mean	0.1875	0.3583	0.1399	0.5235	0.4524	0.7475
	C.I.	0.1428	0.1639	0.04315	0.03791	0.09642	0.04556
30 seeds	Mean	0.1790	0.3527	0.1370	0.5202	0.4287	0.7595
	C.I.	0.0551	0.0653	0.0167	0.0156	0.0415	0.0194
RAT (s)							
With P.M.							
5 seeds	Mean	129.922	134.097	215.288	195.189	178.542	186.949
	C.I.	10.236	10.610	12.326	15.519	16.296	12.953
30 seeds	Mean	125.676	138.484	213.515	207.896	178.794	184.845
	C.I.	4.970	4.947	5.981	6.0117	7.616	6.138
Without P.M.							
5 seeds	Mean	52.221	91.979	54.925	134.405	90.367	155.215
	C.I.	36.460	43.448	30.859	12.670	29.243	19.459
30 seeds	Mean	55.469	92.662	67.431	126.133	93.120	160.211
	C.I.	15.591	17.707	13.299	5.745	12.170	7.799
E2E (s)							

With P.M.							
5 seeds	Mean	0.5963	0.4231	0.0743	0.1269	0.1545	0.3174
	C.I.	0.1314	0.11706	0.0408	0.0758	0.0832	0.1701
30 seeds	Mean	0.5762	0.4482	0.0737	0.08347	0.1453	0.2627
	C.I.	0.0646	0.0411	0.0193	0.0254	0.0276	0.0566
Without P.M.							
5 seeds	Mean	1.2394	0.4026	1.5247	0.6782	0.9525	0.2945
	C.I.	36.460	43.448	30.859	12.670	29.243	0.0944
30 seeds	Mean	1.3568	0.4762	1.8766	0.820	1.0538	0.3237
	C.I.	0.5468	0.1870	0.3704	0.0837	0.1841	0.0539
NRL							
With P.M.							
5 seeds	Mean	1.7628	2.5814	2.0633	4.1438	11.1339	20.2829
	C.I.	0.0532	0.0391	0.0669	0.1047	0.2496	0.7114
30 seeds	Mean	1.8860	2.6462	1.9964	5.2214	11.5078	18.3319
	C.I.	0.0242	0.0131	0.0189	0.0133	0.1205	0.2064
Without P.M.							
5 seeds	Mean	6.1176	4.5756	62.7165	26.2550	36.4604	20.8193
	C.I.	0.0615	0.0280	1.2346	0.3189	0.5694	0.3104
30 seeds	Mean	6.2507	4.5251	61.4516	25.6496	40.6906	19.8507
	C.I.	0.0223	0.0255	0.6222	0.1706	0.3172	0.1527

Table 25 Statistics measures for performance metrics vs number of nodes – AODV

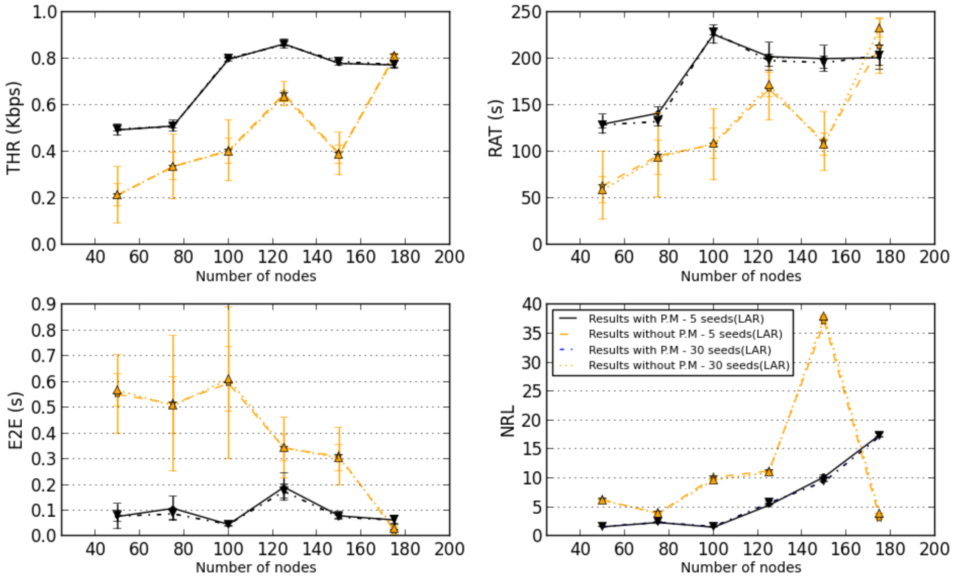

Figure 29 Results of the density analysis – LAR

Figure 29 shows the simulation results obtained by LAR routing protocol. Again, the results are better in terms of mean and confidence interval when the proposed methodology is used. Table 26 details the obtained results for the considered performance metrics. Clearly, the dispersion of the results is much better when applying the proposed methodology.

Number of Nodes		**50**	**75**	**100**	**125**	**150**	**175**
LAR							
THR (Kbps)							
With P.M.							
5 seeds	Mean	0.4937	0.5106	0.7982	0.8645	0.7805	0.7742
	C.I.	0.0248	0.0248	0.0081	0.0199	0.0111	0.0147
30 seeds	Mean	0.4971	0.5092	0.8027	0.8607	0.7892	0.7758
	C.I.	0.0110	0.0085	0.0036	0.0086	0.0049	0.0129
Without P.M.							
5 seeds	Mean	0.2126	0.3354	0.4046	0.6482	0.3897	0.8138
	C.I.	0.1216	0.1399	0.1319	0.0522	0.0921	0.0088
30 seeds	Mean	0.2127	0.3359	0.4018	0.6372	0.3871	0.8103
	C.I.	0.0488	0.0577	0.0537	0.0231	0.0377	0.0049
RAT (s)							

With P.M.							
5 seeds	Mean	129.663	141.456	226.402	202.442	200.400	195.022
	C.I.	10.422	6.730	10.149	15.102	13.779	15.099
30 seeds	Mean	128.843	132.460	228.495	198.159	196.056	198.251
	C.I.	4.178	5.208	3.607	6.948	6.499	12.926
Without P.M.							
5 seeds	Mean	63.128	95.711	107.442	167.329	111.023	213.585
	C.I.	36.520	45.289	38.419	33.477	31.526	29.885
30 seeds	Mean	58.743	93.597	108.845	171.429	108.019	233.413
	C.I.	14.230	18.272	16.127	13.114	12.103	9.905
E2E (s)							
With P.M.							
5 seeds	Mean	0.0775	0.1088	0.0465	0.1914	0.0800	0.0637
	C.I.	0.0491	0.0476	0.0083	0.0529	0.0155	0.0184
30 seeds	Mean	0.0789	0.0874	0.0469	0.1750	0.0745	0.0635
	C.I.	0.0208	0.0209	0.0042	0.0268	0.0070	0.0155
Without P.M.							
5 seeds	Mean	0.5509	0.5156	0.5943	0.3431	0.3102	0.0200
	C.I.	0.1520	0.2632	0.2938	0.1173	0.1114	0.0133
30 seeds	Mean	0.5671	0.5084	0.6103	0.3442	0.3042	0.0304
	C.I.	0.0614	0.1107	0.1272	0.0503	0.0495	0.0088
NRL							
With P.M.							
5 seeds	Mean	1.6561	2.4092	1.5935	5.3808	10.2996	17.5420
	C.I.	0.0331	0.0158	0.0450	0.0611	0.2137	0.4014
30 seeds	Mean	1.6730	2.4378	1.7024	5.7667	9.4928	17.3109
	C.I.	0.0172	0.0085	0.0176	0.1775	0.0836	0.3438
Without P.M.							
5 seeds	Mean	6.2837	4.0053	10.174	11.323	37.003	3.0392

				3	0	2	
	C.I.	0.0204	0.1096	0.2588	0.1663	0.4880	0.1148
30 seeds	Mean	6.2066	3.9803	9.7491	11.0045	37.9442	3.9316
	C.I.	0.0154	0.0432	0.1069	0.0637	0.1834	0.0625

Table 26 Statistics measures for performance metrics vs number of nodes – LAR

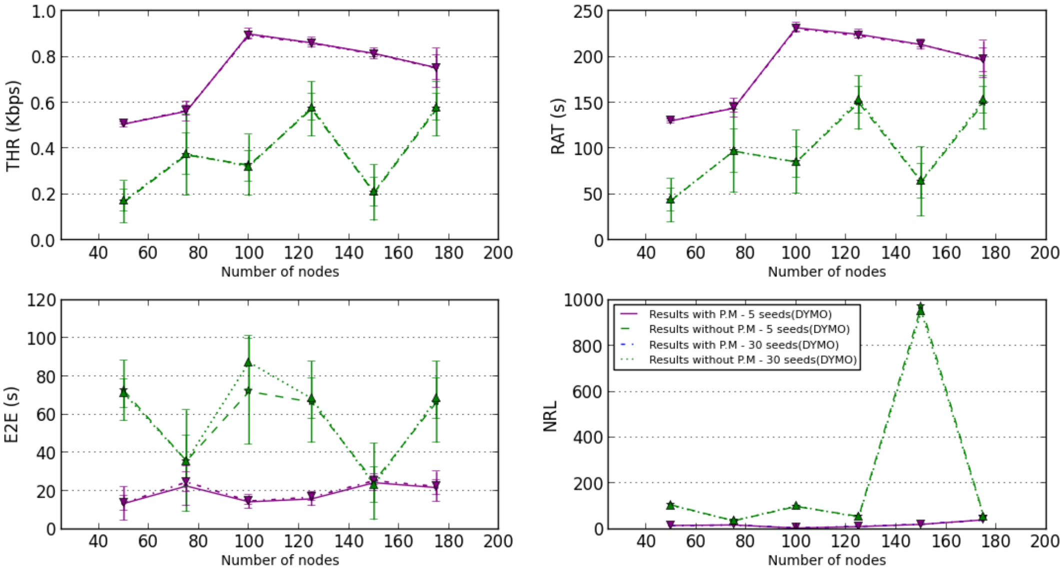

Figure 30 Results of the density analysis – DYMO

In Figure 30 we depict the performance metrics obtained by DYMO routing protocol. We can see that the results are less dispersed when using the proposed methodology. (For more details see Table 27).

Number of Nodes		50	75	100	125	150	175
DYMO							
THR (Kbps)							
With P.M.							
5 seeds	Mean	0.5072	0.5630	0.8998	0.8614	0.8150	0.7526
	C.I.	0.0128	0.0432	0.0237	0.0214	0.0230	0.0531
30 seeds	Mean	0.5082	0.5658	0.8944	0.8594	0.8124	0.7509
	C.I.	0.0046	0.0220	0.0123	0.0114	0.0129	0.0854
Without P.M.							
5 seeds	Mean	0.1673	0.3726	0.3272	0.5729	0.2074	0.57296
	C.I.	0.0915	0.1760	0.1337	0.1195	0.1220	0.1195
30 seeds	Mean	0.17208	0.3769	0.3218	0.5801	0.2110	0.5801
	C.I.	0.0471	0.0906	0.065	0.065	0.0610	0.0585
RAT (s)							
With P.M.							
5 seeds	Mean	130.313	144.058	231.801	224.562	213.445	196.274
	C.I.	2.622	10.636	5.109	4.745	5.477	13.171
30 seeds	Mean	130.313	144.058	231.801	224.562	213.445	196.274
	C.I.	0.942	5.364	2.736	2.623	3.068	20.344
Without P.M.							
5 seeds	Mean	43.5044	97.3636	85.4762	149.915	63.9673	149.915
	C.I.	23.812	45.655	34.359	29.379	37.765	29.379
30 seeds	Mean	44.140	97.305	85.132	152.88	64.647	152.884
	C.I.	12.0723	23.180	16.961	14.523	18.705	14.523
E2E (s)							
With P.M.							
5 seeds	Mean	13.5061	22.6450	14.3689	15.9048	24.3982	21.8087

	C.I.	8.7146	10.5515	3.4104	3.6844	4.2207	3.8601
30 seeds	Mean	13.7178	24.7080	14.8118	16.7940	25.4729	22.4098
	C.I.	3.9479	5.0503	1.8438	2.0516	2.4619	7.8033
Without P.M.							
5 seeds	Mean	72.580	35.7447	72.0954	66.6104	25.0120	66.6104
	C.I.	15.8187	26.6106	27.5796	21.3251	20.1057	21.3251
30 seeds	Mean	71.082	35.7670	87.3907	68.4805	23.2911	68.4805
	C.I.	3.9479	5.0503	1.8438	2.0516	2.4619	7.8033
NRL							
With P.M.							
5 seeds	Mean	16.5322	18.9819	5.2775	11.8661	21.4601	41.2694
	C.I.	0.1695	0.0988	0.2035	0.4036	0.2306	0.6688
30 seeds	Mean	16.3235	18.8010	5.8642	12.6981	21.8431	40.9412
	C.I.	0.0621	0.0429	0.1149	0.2070	0.3080	1.4560
Without P.M.							
5 seeds	Mean	106.389	37.094	99.383	56.251	972.050	56.2519
	C.I.	1.553	0.194	1.770	1.195	10.362	1.1956
30 seeds	Mean	104.413	36.853	102.026	53.286	950.433	53.2866
	C.I.	1.120	0.083	1.033	0.668	7.617	1.4560

Table 27 Statistics measures for performance metrics vs number of nodes – DYMO

5.2.2.2. Congestion analysis

In this study we vary the number of connections, in steps of 5 connections each, within the interval [5, 25]. The number of nodes of the network is fixed to 125 nodes (high density scenario) and the APA values and the number of hops are the same than those selected in the previous analysis (See Table 14 and Table 16 for more details).

Figure 31 shows the simulation results for THR, RAT, E2E, NRL performance metrics with their confidence intervals for each number of nodes. Figure 31 includes the results using the proposed methodology (Results with P.M in Figure 31) and without using the proposed methodology (Results without P.M in Figure 31). Once again, we depict the results for 5 and 30 simulations and we verify that using the proposed methodology more reliable results are obtained despite of using a lower number of simulations (See Table 28 for more details)

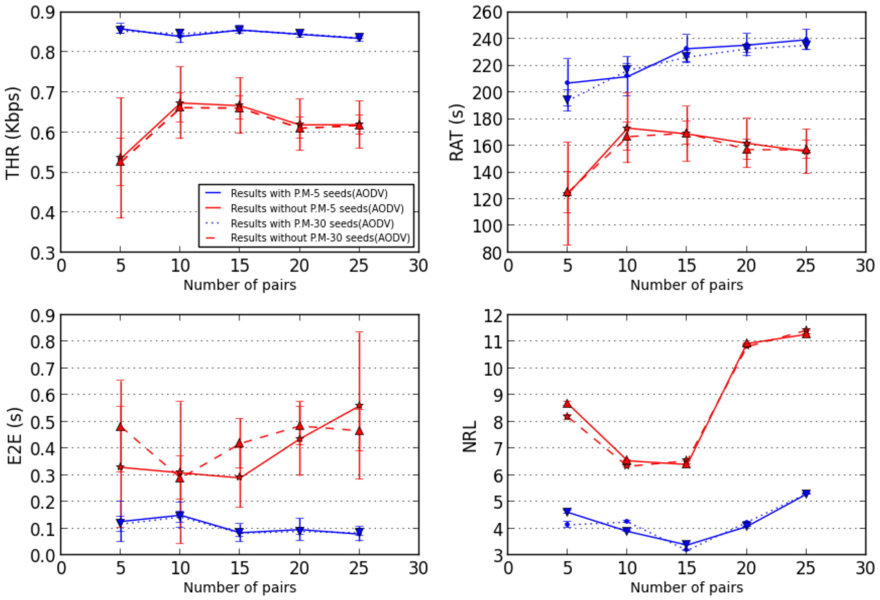

Figure 31 Results of the congestion analysis - AODV

Number of Pairs		5	10	15	20	25
AODV						
THR (Kbps)						
With P.M.						
5 seeds	Mean	0.8582	0.8392	0.8557	0.8448	0.8346
	C.I.	0.0119	0.0160	0.0098	0.0082	0.0086
30 seeds	Mean	0.8526	0.8464	0.8546	0.8461	0.8359
	C.I.	0.0063	0.0061	0.0036	0.0036	0.0035
Without P.M.						
5 seeds	Mean	0.5355	0.6735	0.6664	0.6187	0.6193
	C.I.	0.1504	0.0898	0.0700	0.0637	0.0590
30 seeds	Mean	0.5262	0.6615	0.6608	0.6104	0.6173

	C.I.	0.0591	0.0360	0.0292	0.0261	0.0238
RAT (s)						
With P.M.						
5 seeds	Mean	206.923	211.773	232.659	235.301	239.376
	C.I.	17.771	14.754	10.157	8.420	7.762
30 seeds	Mean	193.780	216.385	226.776	232.539	235.134
	C.I.	8.019	5.125	4.387	3.316	3.182
Without P.M.						
5 seeds	Mean	124.043	173.201	168.820	161.880	155.708
	C.I.	38.520	26.256	20.532	18.419	16.549
30 seeds	Mean	125.124	166.788	169.387	157.127	156.794
	C.I.	15.413	10.331	8.578	7.420	6.730
E2E (s)						
With P.M.						
5 seeds	Mean	0.1269	0.1505	0.0850	0.0966	0.07975
	C.I.	0.0758	0.0459	0.0327	0.0409	0.0272
30 seeds	Mean	0.1173	0.1436	0.0831	0.0894	0.0844
	C.I.	0.0274	0.0202	0.0135	0.0130	0.0131
Without P.M.						
5 seeds	Mean	0.3297	0.3092	0.2902	0.4364	0.5598
	C.I.	0.2257	0.2650	0.1108	0.1386	0.2744
30 seeds	Mean	0.4817	0.2895	0.4189	0.4846	0.4668
	C.I.	0.1710	0.0802	0.0922	0.0723	0.0766
NRL						
With P.M.						
5 seeds	Mean	4.1438	4.2499	3.1861	4.2388	5.3047
	C.I.	0.1047	0.0385	0.0181	0.0222	0.0142

						7
30 seeds	Mean	4.6115	3.8982	3.3883	4.0784	5.2930
	C.I.	0.0623	0.0186	0.0093	0.0069	0.0055
Without P.M.						
5 seeds	Mean	8.1798	6.3340	6.5440	10.8139	11.4277
	C.I.	0.0938	0.0269	0.0368	0.01402	0.0282
30 seeds	Mean	8.6758	6.5426	6.4049	10.9307	11.2774
	C.I.	0.0649	0.0224	0.0113	0.0107	0.0101

Table 28 Statistics measures for performance metrics vs number of pairs – AODV

Figure 32 shows again that a smoother tendency is obtained for the congestion analysis when the proposed methodology is used. Similarly, the confidence intervals obtained with the proposed methodology are lower than those obtained when it is not applied. In this analysis (See Figure 32) the proposed methodology also provides better results as the network congestion increases (See Table 29 for more details).

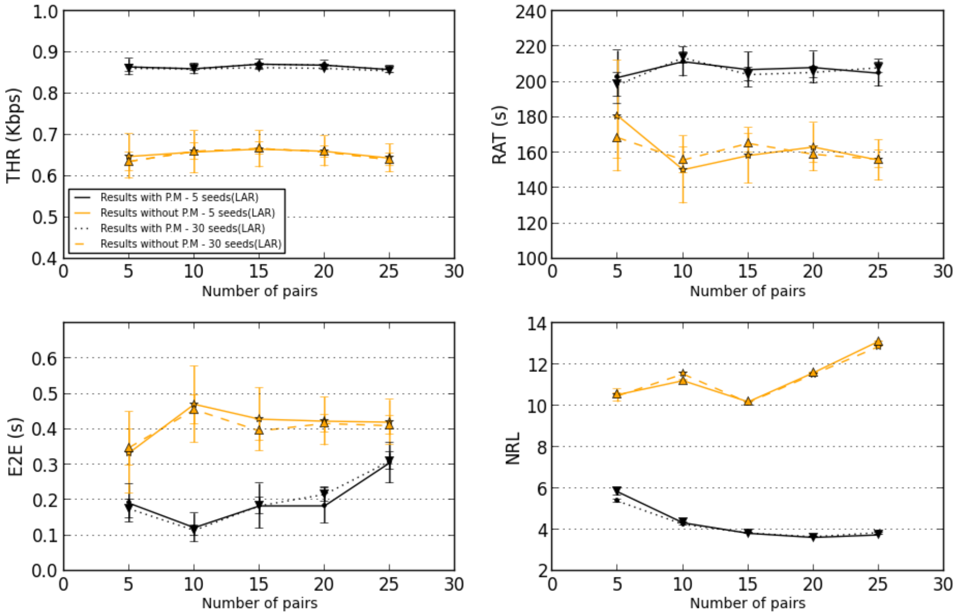

Figure 32 Results of the congestion analysis - LAR

Number of Pairs		**5**	**10**	**15**	**20**	**25**
LAR						
THR (Kbps)						
With P.M.						
5 seeds	Mean	0.8645	0.8601	0.8712	0.8688	0.8581
	C.I.	0.0199	0.0133	0.0112	0.0098	0.0093
30 seeds	Mean	0.8610	0.8595	0.8628	0.8611	0.8549
	C.I.	0.0080	0.0054	0.0043	0.0036	0.0041
Without P.M.						
5 seeds	Mean	0.6477	0.6585	0.6656	0.6603	0.6436
	C.I.	0.0539	0.0513	0.0440	0.0365	0.0339
30 seeds	Mean	0.6356	0.6601	0.6669	0.6591	0.6396
	C.I.	0.0224	0.0199	0.0157	0.0132	0.0141
RAT (s)						
With P.M.						
5 seeds	Mean	202.442	211.412	206.878	208.050	204.882
	C.I.	15.102	8.350	9.819	8.958	7.529
30 seeds	Mean	198.321	213.621	204.071	205.322	207.927
	C.I.	6.601	3.203	3.925	3.100	3.084
Without P.M.						
5 seeds	Mean	180.722	150.339	158.320	163.162	155.743
	C.I.	31.306	19.054	15.669	13.654	11.530
30 seeds	Mean	168.474	155.804	165.221	159.049	156.168
	C.I.	11.681	7.366	5.427	4.736	4.811
E2E (s)						
With P.M.						

5 seeds	Mean	0.1914	0.1224	0.1837	0.1839	0.3057
	C.I.	0.0529	0.0405	0.0629	0.0483	0.0574
30 seeds	Mean	0.1757	0.1148	0.1840	0.2163	0.3102
	C.I.	0.0256	0.0146	0.0228	0.0207	0.0241
Without P.M.						
5 seeds	Mean	0.3338	0.4709	0.4289	0.4231	0.4204
	C.I.	0.1161	0.1082	0.0889	0.0680	0.0630
30 seeds	Mean	0.3486	0.4558	0.3957	0.4167	0.4104
	C.I.	0.0510	0.0414	0.0290	0.0251	0.0259
NRL						
With P.M.						
5 seeds	Mean	5.3808	4.2594	3.8384	3.6584	3.8578
	C.I.	0.061	0.047	0.015	0.006	0.006
30 seeds	Mean	5.8295	4.3325	3.8238	3.6221	3.7453
	C.I.	0.1699	0.0357	0.0063	0.0047	0.0035
Without P.M.						
5 seeds	Mean	10.4852	11.5379	10.1581	11.5247	12.8672
	C.I.	0.2965	0.0612	0.0271	0.0124	0.0283
30 seeds	Mean	10.539	11.216	10.192	11.598	13.123
	C.I.	0.0804	0.0252	0.0144	0.0080	0.0072

Table 29 Statistics measures for performance metrics vs number of pairs – LAR

Regarding DYMO routing protocol (See Figure 33), the results are also not dispersed. They are better (in terms of mean) and we can see a smoother tendency of the performance metrics applying the proposed methodology (For more details see Table 30).

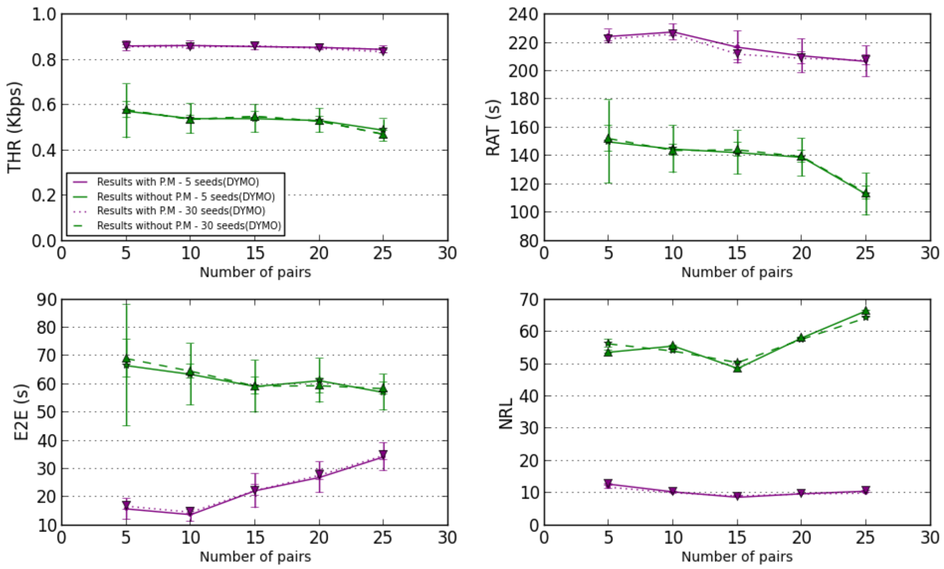

Figure 33 Results of the congestion analysis – DYMO

Number of Pairs		**5**	**10**	**15**	**20**	**25**
DYMO						
THR (Kbps)						
With P.M.						
5 seeds	Mean	0.8614	0.8636	0.8587	0.8551	0.8461
	C.I.	0.0214	0.01693	0.0164	0.0134	0.0146
30 seeds	Mean	0.8585	0.8554	0.8620	0.8502	0.8354
	C.I.	0.0071	0.0047	0.0053	0.0045	0.0056
Without P.M.						
5 seeds	Mean	0.5729	0.5400	0.5398	0.5315	0.4884
	C.I.	0.1195	0.0664	0.0620	0.0535	0.0484
30 seeds	Mean	0.5780	0.5368	0.5495	0.5290	0.4703
	C.I.	0.0360	0.0154	0.0200	0.0176	0.0159
RAT (s)						
With P.M.						
5 seeds	Mean	224.562	227.734	216.916	210.874	206.888

	C.I.	4.745	5.709	11.521	11.972	10.794
30 seeds	Mean	222.868	226.217	211.986	209.079	207.642
	C.I.	1.628	1.573	4.525	4.117	3.691
Without P.M.						
5 seeds	Mean	149.915	144.814	142.371	139.053	112.827
	C.I.	29.379	16.855	15.374	13.429	14.962
30 seeds	Mean	152.285	143.882	144.351	139.452	113.793
	C.I.	8.972	3.864	4.987	4.419	4.910
E2E (s)						
With P.M.						
5 seeds	Mean	15.9048	13.8787	22.3367	27.0592	34.3470
	C.I.	3.6844	2.5246	6.1019	5.4334	5.0076
30 seeds	Mean	16.8680	14.7454	22.4142	27.8414	34.8339
	C.I.	1.2619	0.7011	1.9091	1.7882	1.6750
Without P.M.						
5 seeds	Mean	66.6104	63.5052	59.2219	61.2661	57.1043
	C.I.	21.3251	10.8777	9.2749	7.7797	6.4067
30 seeds	Mean	69.0914	64.6261	59.3388	59.4877	58.4515
	C.I.	6.6084	2.4876	2.9497	2.5537	2.1852
NRL						
With P.M.						
5 seeds	Mean	11.8661	10.1422	9.2064	9.7781	10.0558
	C.I.	0.4036	0.0658	0.0688	0.0222	0.0162
30 seeds	Mean	12.8203	10.4430	8.7722	9.8621	10.6552
	C.I.	0.1274	0.0199	0.0185	0.0102	0.0092

Without P.M.						
5 seeds	Mean	56.2519	54.0320	50.4579	57.7146	64.3516
	C.I.	1.1956	0.3271	0.1449	0.0851	0.1476
30 seeds	Mean	53.6853	55.5944	48.6554	58.1439	66.5199
	C.I.	0.4110	0.0921	0.0678	0.0417	0.0497

Table 30 Statistics measures for performance metrics vs number of pairs – DYMO

5.2.2.3. Comparison of the routing protocols using the proposed methodology

This subsection is aimed at providing a fair an unbiased comparison between the three used routing protocols such as AODV, DYMO, and LAR. We evaluate the mentioned routing protocols under different network conditions using the proposed APA metric and number of hops. In Figure 34 we depict the throughput and NRL metrics for AODV, LAR and DYMO for different APA values. We vary the APA value in steps of 0.2. As it is shown in Figure 34, the throughput of the three routing protocols increases as the APA value also increases because the routes between source and destination nodes are available during more time. As a consequence, the number of delivery packets is higher. According to the results, DYMO has the best performance metrics for high APA values while LAR is the best one for low APA values. However the NRL decreases when the APA value increases because is not necessary to initiate new discovery phases due to the fact that the routes are more time available so the number of routing packets decreases. In terms of NRL, DYMO presents the worst behaviour because the necessary routing information (routing packets) is higher.

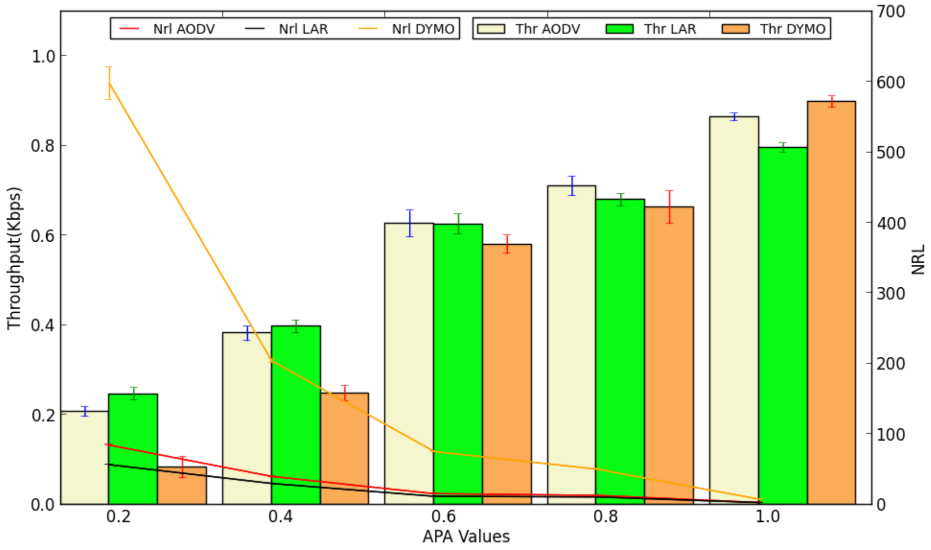

Figure 34 Throughput and NRL vs APA

Now we evaluate the routing protocols versus the number of hops between the source and destination nodes (See Figure 35). We also evaluate the three routing protocols in terms of throughput and NRL metrics. For the three routing protocols, the throughput metric is better for low number of hop values (See Figure 35). This situation corresponds to the one in which the destination node is near the source node (in terms of hops). Consequently, the probability of losing data packets is lower. Yet when the number of hops increases the throughput decreases for the three routing protocols. DYMO has the best performance for low number of hops because this one is able to generate routes entries for each intermediate hop. However, when the distance between source and destination node is higher the routing data packets are also higher. In consequence, the delivery of packets decreases. Regarding the NRL, it increases for the three used routing protocols because the number of discovery phases is higher when the number of hops increases. As we mentioned before DYMO has the worst behaviour because the routing information is higher.

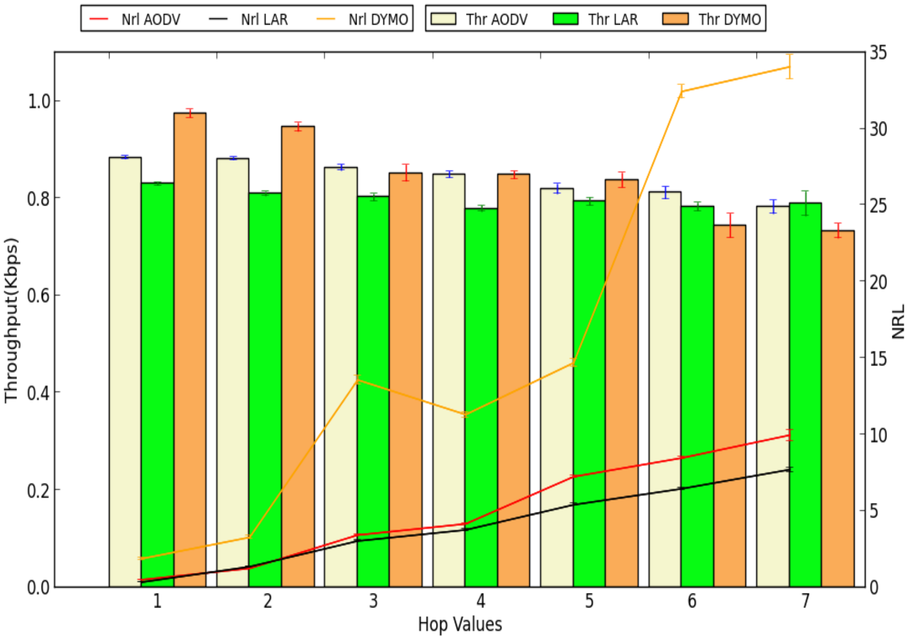

Figure 35 Throughput and NRL vs number of hops

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6. A SIMULATION METHODOLOGY FOR CONDUCTING UNBIASED AND RELIABLE EVALUATION OF MANET COMMUNICATION PROTOCOLS IN DISASTER SCENARIOS

This chapter presents an evaluation methodology for conducting simulations of routing protocols and broadcasting algorithms for the application of MANETs in disaster scenarios. The proposed methodology is based on the study of the topological properties of the considered scenarios, and the selection of several important simulation parameters. The main idea is to guarantee that the evaluation of communication protocols is fair and statically reliable. The rest of this chapter continues as follows. Section 6.1 introduces the models available for disaster scenarios and the one used in this chapter. Section 6.2 contains the proposed evaluation methodology, and section 6.3 includes the simulation results that validate the proposed methodology.

6.1. Modeling disaster scenarios

Modeling disaster scenarios for carrying out simulation studies is of paramount importance. Normally in MANET simulation studies, mobility models are used to define the movements of nodes during the simulation time. Notice that this fact impacts importantly in the communication among nodes. Therefore, the considered mobility model should reflect real conditions in order to conduct a reliable evaluation of MANETs.

6.1.1. Existing mobility model for disaster scenarios

Nowadays, modeling the behavior of people in catastrophe situations is one of the objectives of the disaster mobility models. However, disaster areas are scenarios where it is difficult to know in detail because the disaster actually changes significantly the previous structure of the area due to broken roads, collapsed buildings, etc. In [1][2], the authors proposed a new mobility model, namely Composite Mobility (CoM), to model the mobility of humans in these situations. This model is based on three different aspects: i) realistic human movements, ii) group mobility and iii) obstacle avoidance. To model the movements of the injured and rescue teams, they use other well-known mobility models like the Levy-Walk [3]. The main reason is that this mobility model is quite realistic for emulating human movements. In addition, to model the movements of the rescue team workers, CoM used the Point Group Mobility (PGM) model [4]. Finally and to solve the obstacle avoidance problems, a modification of Voroni diagrams is used [5].

In [6], the authors propose another mobility model for disaster scenarios which mimics the real movements in search operations. The behavior of rescue workers when performing search-for-victims operations is modeled. The people maintain short distance between them with the objective of discovering new victims and can communicate these discoveries between them. Due to this fact, the authors in [6] propose two different distance values to control the movement of victims. On the one hand *MaxDistance*, an injured person has to be separated to another one by a distance lesser than this value. On the other hand *MinDistance*, the distance between two victims must be higher than this value. When nodes are not within these restrictions, it is defined a force which moves them into an optimal location.

In these situations is also important to model the behavior of the rescue team, specially the first responders. In [7], it is presented CORPS (Cooperation, Organization and Responsiveness in Public Safety) which models the behavior of the first responders. It bases the movements on three different aspects: i) people are organized and follow tactical movements; ii) they cooperate with each other within a group and iii) they present responsiveness to events occurring in the disaster area. Moreover, CORPS is based on three different components: the first responder model, the event model and the interaction model. Each person is labeled with a role and people with the same role compose a group. The event models capture physical events happening in time and space. Each first responder has a role and the first responders with the same role have similar attributes and cooperate on events. These events are classified into two types such as attention and caution events. In the former, injured victims need assistance from the first responders. On the other hand, caution events correspond to situations in which there are not people involved in the accident, for example, chemical spill and explosions. Finally to create the mobility model is necessary the interaction between the first responders and the events. This process is named interaction model. Each first responder sees the incident areas as the sum of attending and forbidden zones and bases his/her movements on these aspects. As we can see CORPS gives a high level of realism to the first responder movements. However the victim movements in the disaster scenario are not model by CORPS

6.1.2. The disaster area mobility model

This model is the so-called Disaster Area mobility [8] model, which is included in the open source mobility generator BonnMotion [8]. Notice that the Disaster Area mobility model defines tactical movements of a rescue team, but it does not take into consideration movements of victims in the disaster area. The Disaster Area mobility model is based on a method called separation of rooms [8]. Using this method, the disaster scenario is divided into different areas. These tactical areas are: (i) *Incident site* is the place where the disaster happened. In this area, people injured are waiting for being rescued and being transported to treatment areas. (ii) *Casualties treatment area*. There are two places in this area. First, the place where patients wait for their treatment, which is named patients waiting for treatment area. And the other one is called the casualties clearing station, where injured people are transported after receiving their first aids. In a casualty treatment area, nodes are waiting for being transported to a hospital. (iii) *Transport zone* is the zone where ambulances and helicopters wait to take injured people and transport them to hospitals. (iv) *Technical operational command zone* is the place where the rescue operations are commanded, normally inside the casualty treatment areas. (v) hospital zone where the vehicles of the transport zone transport the patients to the hospital. Normally these zones are not in the disaster area, for this reason ambulances always leave and join the network at intervals.

All the areas mentioned above are modelled as squares. In each of these squares, the nodes mobility is modelled with the Random Waypoint Mobility model. Each sub-area has entrance points; these are specific locations at the edge of each sub-area that are used by the first responders to move victims from one sub-area to another.

In Figure 36 we show the movements followed by the members of a rescue team in a disaster scenario according to the disaster area mobility model. Each coloured line in Figure 36 represents a different crewmember movement. We also mark each area such as Incident Location (IL), Patient Waiting for Treatment Area (PWFT), Casualty Clearing Station (CCS), Technical operation area (TEL), and Ambulance Parking area (APP).

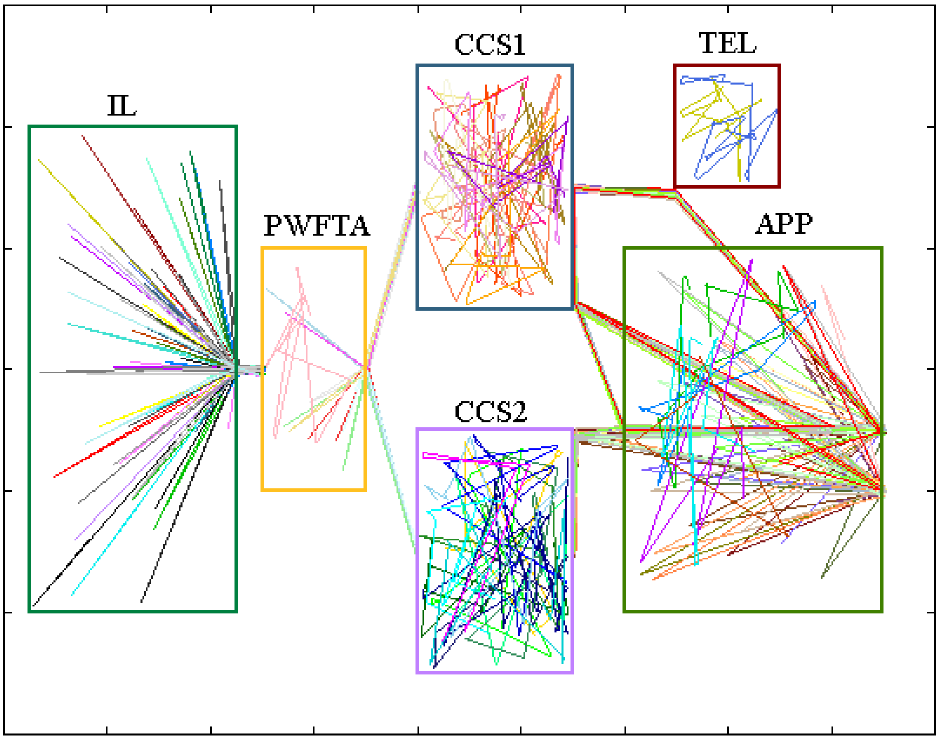

Figure 36 Disaster area movements

The Disaster Area mobility model has already been used to simulate the movements of crewmembers in real disaster scenarios such as the disaster in Germany in 2005 during the preparation of the World Youth Day 2005, the FIFA Soccer World Cup 2006 [9], the disaster scenario based on a suspension railway crash that happened in Wurppertal in 1999 [10], and the disaster scenario based on a fire in amusement park near Cologne in 2001 [10].

Disaster Area mobility model is one of the most used mobility models to evaluate communications protocols in disaster scenarios. For this reason, we will use this model in this chapter. However, other mobility models are available and they could be used in future works to apply the proposed methodology.

6.1.3. Communications in the disaster area mobility model: inter-communications vs intra-communications

Since crewmembers in the disaster area mobility model are grouped into different areas, we consider two possible types of communications among them such as i) inter-communications and ii) intra-communication. The former type of communications is established between two nodes that are moving inside different zones or tactical areas. For instance, this kind of communications can be established between the transport zone and the hospital zone to coordinate the transport of an injured person (see Figure 36).Intra-communications are established between two nodes that are located inside the same zone. For instance, two firefighters moving inside the incident location area. It is obvious that path availability can be significantly different for inter-communications and intra-communications due to fact that the distances between the people inside the same area are much smaller than the distances between two different areas. Figure 37 depicts two examples of the movements of source nodes for the two types of communications described.

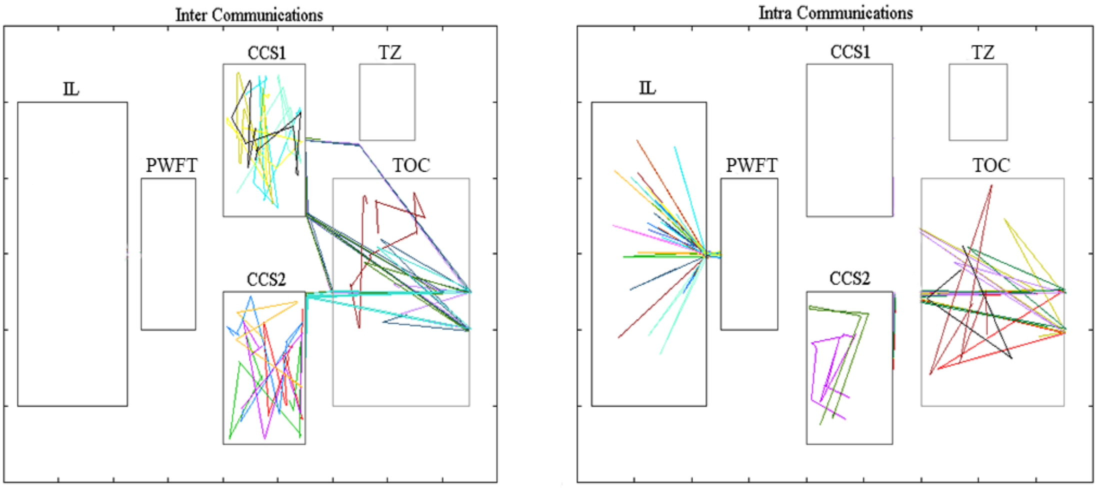

Figure 37 Example of source movements for inter and intra communication

6.2. The proposed evaluation methodology for evaluating communication protocols in disaster scenarios

This section describes the proposed evaluation methodology. We divide the proposed methodology into two subsections, one focused on routing protocols, and another on broadcasting algorithms.

6.2.1. Evaluation methodology for MANET routing protocols in disaster scenarios

The idea is to apply the methodology proposed in chapter 5 to disaster scenario (from now on the scenario under test.

6.2.1.1. Communication set up

Based on the previous chapter proposed methodology, it is necessary to use warm up period to obtain reliable and non-dispersed simulation results. For that, we depict in Figure 5 different values of Warm Up periods (from 0 to 100s). Then, we use the Throughput metric (THR in Figure 38) which measures the number of application delivered packets during the simulation time, the performance metrics are defined in Section 5.1.5. In this study, we select 5 different source and destination nodes randomly and we do not distinguish between intra and inter communications. We can see in Figure 38 as the Warm up value increases, the THR also increases. It is due to the fact that the number of source nodes that have started to transmit packets is higher. We can observe that from 50s (see Table 31 for more details) the THR values are the same. Related to the confidence intervals, they are very similar and high because the source and destination pairs are selected randomly. From now on, we consider 50s as the Warm Up value for the scenario under test.

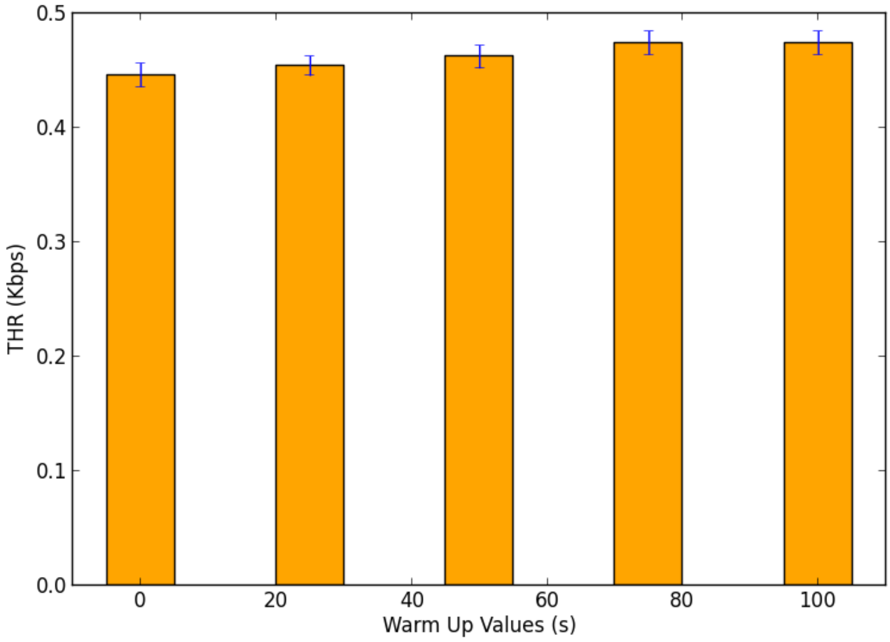

Figure 38 THR vs Warm Up Values

Warm up Values (s)	0	25	50	75	100
THR (Kbps)					
Mean	0.4461	0.4540	0.4620	0.4742	0.4742
Confidence interval	0.0103	0.0086	0.090	0.01028	0.01029

Table 31 THR vs Warm up values

6.2.1.2. Communication flow selection

Next, we show how to apply the proposed methodology in scenario under test. The procedure is as follows: First, we obtain the distribution of the APA and number of hops for all the possible communication pairs (source-destination). Then, we select the most representative values for both metrics. Finally, we benchmark the performance of AODV routing protocol (baseline routing protocol) to show the importance of both metrics in the performance of routing protocols.

6.2.1.2.1. APA distribution

The first step is to measure the APA distribution in the scenario under test in order to fix the target APA. Since we have considered two types of communications (inter and intra communications), we have two possible APA distributions, one distribution for inter-communications and another for intra-communications. It is expectable to have low values of the APA distribution for inter-communications; however there can be some of them with higher APA value. In the APA distribution for intra-communication case, it is expectable that the most pairs will have a high APA value. To show this situation we depict (see Figure 39) the APA distribution for intra and inter communications.

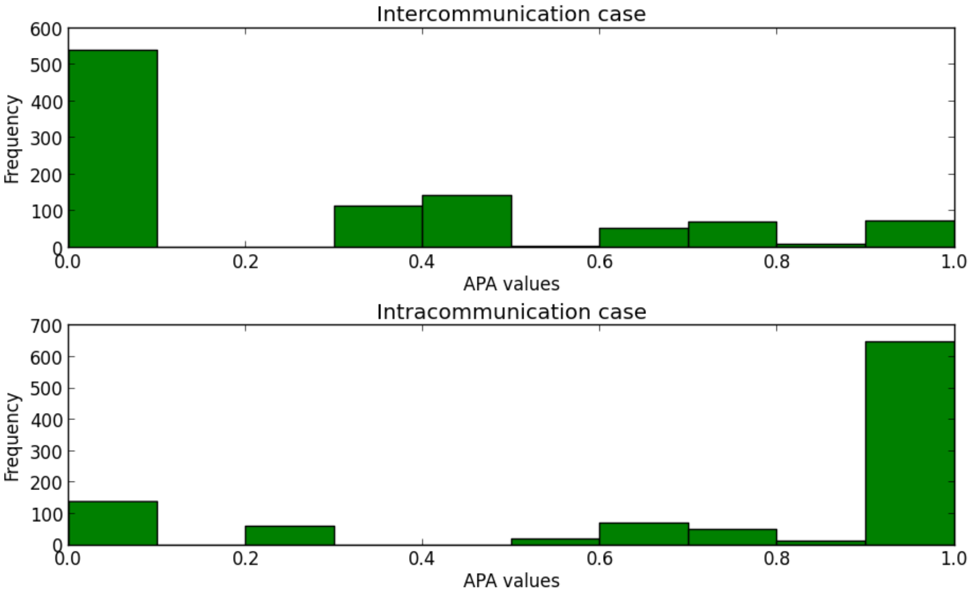

Figure 39 APA distribution for Inter and Intra communication

As we can see in Figure 39, most of APA values for Intercommunication case are zero. It means that the communications between areas are not possible because these areas are widely separated. Related to the target APA, we can set this one in 0.4 due to the fact that we can ensure a high number of pairs with this value. In the intra communication case, we can set the target APA in 0.7. Obviously the value 1.0 is the best one but this situation can correspond to destination nodes which are within the source transmission range node and the routing protocols are not necessary. For this reason, we select 0.7 as the target APA which we can obtain a high number of pairs, around 100.

6.2.1.2.2. Hop distribution

After selecting pairs based on the APA, the next step is to select pairs based on the distance in terms of number of hops. For that, we choose a target hop which ensures pairs which are separated by the same or similar number of hops. In this step, we also distinguish between intra-communication and inter-communication. For both cases, we want to select pairs that have the highest separation in order to ensure a multi-hop path. Similar to the previous APA distribution section, we also should ensure that there are enough source-destination pairs. In Figure 40 we can see the hop distribution for both cases.

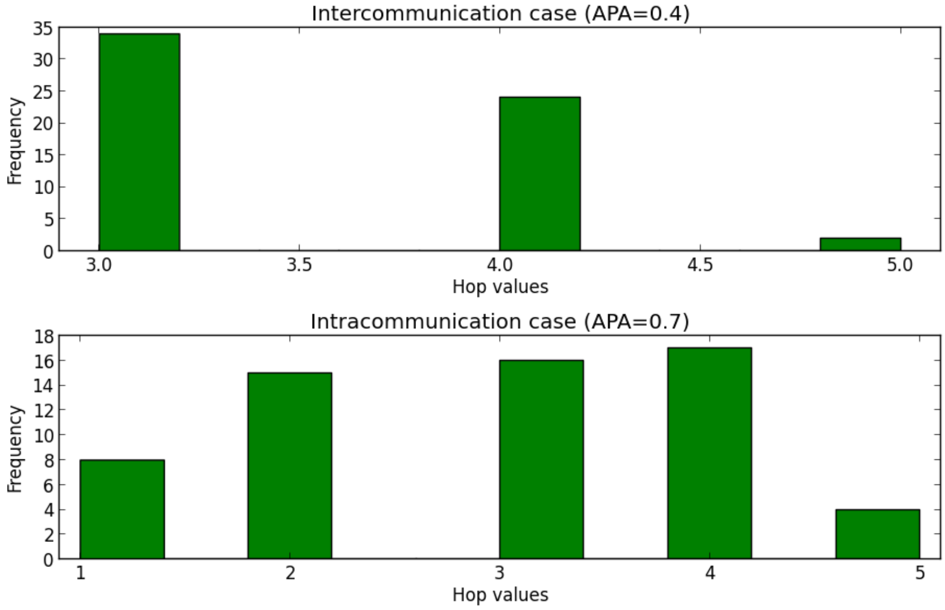

Figure 40 Hop distribution for Inter and Intra communication

The idea is to select a target hop value from the highest possible value that ensures a high number of available pairs. As we can see in Figure 40, this value corresponds to 4 hops for both cases. Table 32 summarizes the proposed source destination node selection.

	Target APA	Target Hop

Intra Communication	0.4	4
Inter Communication	0.7	4

Table 32 Source destination selection summary

6.2.1.3. Number of simulations

The motivation for this idea is not to devote more time than necessary to conduct simulations while ensuring good results in terms of mean and dispersion. For that reason we have to select a number of simulations that ensure a representative data sample without requiring a lot of simulation time. In consequence, we have to reach a balance between the number of simulations and computing time. Figure 41 shows the throughput results (THR) and the required computing time for different number of traffic seeds (number of simulations). For this study we use the same scenario than in previous studies (the scenario under test) and we use five different pairs, the selection of these pairs are based on the proposed methodology. Orange bars represent the selected pairs based on the used methodology and yellow bars represent the random selection (See Figure 41). In Figure 41 we distinguish between intra and inter communications. We can see in both cases, intra and inter communication cases, that the results are lesser scattered in the case of applying the proposed methodology (vertical interval in Figure 41) than in the case of not using this methodology (vertical green interval in Figure 41). We can see that for low number of simulations, we can obtain simulation results which are not scattered (see Table 33 for more details). If we compare the results with high number of simulations the differences are smaller. Consequently, we can select 5 as the best number of simulations due to the fact that we obtain good results in terms of dispersion and the computing time is low as well.

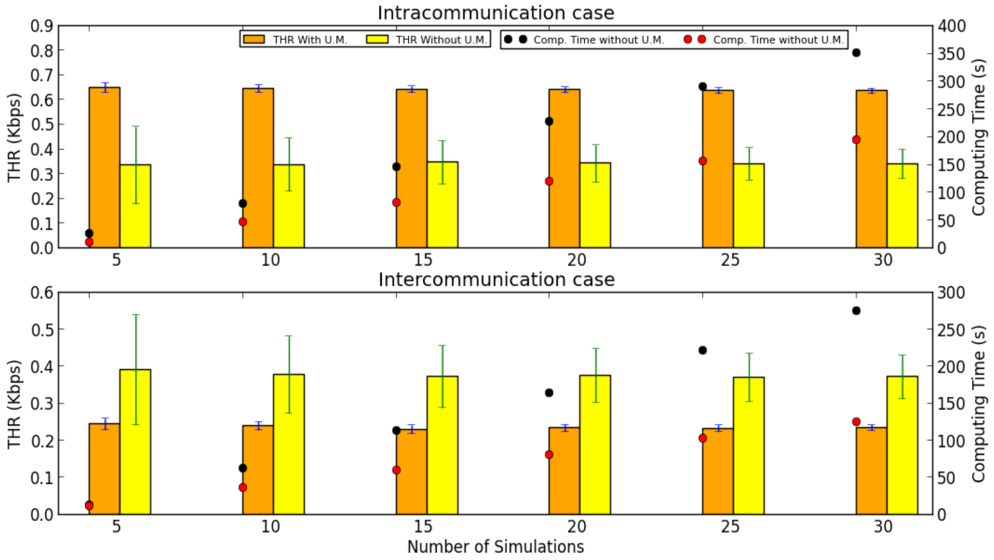

Figure 41 THR vs Number of simulations

Using the Methodology						
Intra Communications						
Nº Simulations	**5**	**10**	**15**	**20**	**25**	**30**
THR (Kbps)						
Mean	0.6493	0.6454	0.6415	0.6394	0.6355	0.6353
Confidence interval	0.0203	0.0155	0.0132	0.0116	0.0111	0.0102
Computing time (s)						
Inter Communications						
THR (Kbps)						
Mean	0.2437	0.2392	0.2296	0.2331	0.2325	0.2342
Confidence Interval	0.0156	0.0115	0.0113	0.0098	0.0088	0.0076
Computing time (s)						
	26.26	80.96	145.32	228.69	290.55	351.14
Not using the Methodology						
Intra Communications						
Nº Simulations	**5**	**10**	**15**	**20**	**25**	**30**
THR (Kbps)						
Mean	0.3339	0.3373	0.3472	0.3414	0.3390	0.3397
Confidence interval	0.1565	0.1085	0.0880	0.0749	0.0660	0.0597
Computing time (s)						
	13.25	62.58	113.66	164.59	221.77	275.89
Inter Communications						
THR (Kbps)						
Mean	0.3915	0.3768	0.3720	0.3760	0.3698	0.3712
Confidence Interval	0.1490	0.1045	0.0842	0.0730	0.0650	0.0591
Computing time (s)						
	9.41	45.75	81.62	119.08	155.36	194.04

Table 33 Statistics measures for THR vs number of simulations

6.2.1.4. Benchmarking the methodology with AODV routing protocol in the disaster scenario

In this subsection we use AODV as standard routing protocol to benchmark the proposed methodology. We evaluate AODV using the proposed APA metric and the number of hops. In this case, we also distinguish between intra and inter communications. We use the throughput and the NRL metrics, which measures the congestion of the network.

To highlight the importance of the APA in the performance of the routing protocols, we depict in Figure 42 the throughput (THR in Figure 42) for different values of APA, for inter and intra communication cases (orange bars in Figure 42). We also depict the obtained results when we do not use the methodology, NUUM (Not using the used methodology), (yellow bar in Figure 42). For this analysis, we select APA values that ensure a minimum number of pairs (Figure 39). We also add another restriction in the selection of the pairs based on APA values such as the fact that the communication pairs cannot be repeated. In Figure 42 we can see that as the APA value increases the number of delivery packets also increases due to fact that the available path is higher. The tendencies in both cases are to increase as the APA value also increases. Related to NUUM results, we can see that the results are worst in terms of mean and also they are more scattered (blue interval in Figure 42). Table 34 contains more details about the obtained results.

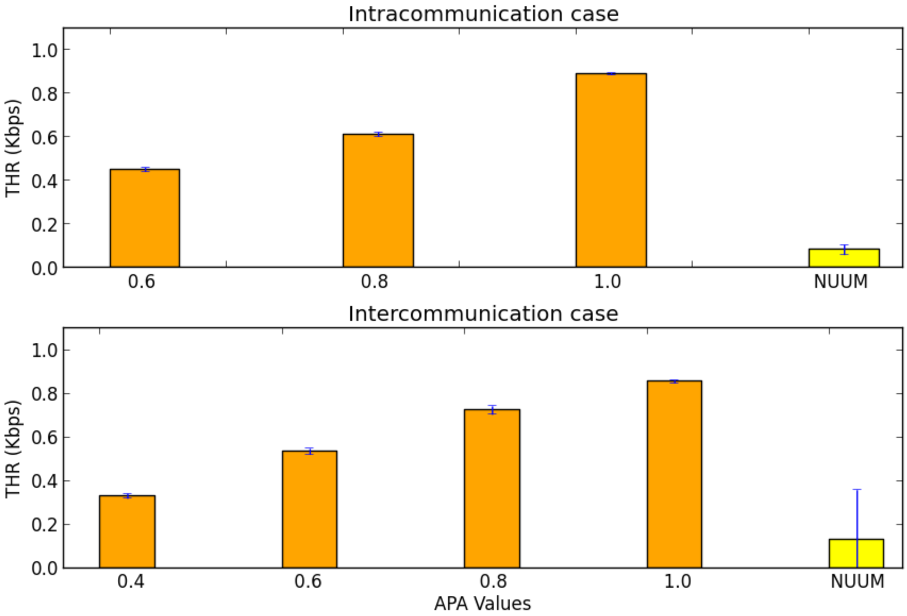

Figure 42 Throughput vs APA

Intra Communication				
APA value	**0.6**	**0.8**	**1.0**	**NUUM**
THR (Kbps)				
Mean	0.4498	0.6113	0.8895	0.08172
Confidence interval	0.0092	0.0103	0.0039	0.0233

Inter Communication					
APA value	**0.4**	**0.6**	**0.8**	**1.0**	**NUUM**
THR (Kbps)					
Mean	0.3294	0.5333	0.7226	0.8540	0.1313
Confidence interval	0.0116	0.0134	0.0193	0.0059	0.2260

Table 34 THR vs APA values in the scenario under test

Second, we study the performance of AODV based on the number of hops. Again, we use the THR (orange and yellow bars in Figure 43 respectively) and the NRL metrics (red points in Figure 43). We can see in Figure 43 that as the number of hops increases as the number of delivery packets decreases in both of cases. The reason is that the number of lost packets increases. Regarding the congestion, the NRL increases when the numbers of hops increases. This situation happens in both types of communications because the number of routing packets is higher. Next we focus on the NUUM results, for intra and inter communication cases. In the intra communication the THR mean is lower and more scattered (see vertical blue intervals in Figure 43) than when using the proposed methodology. The reason is that the selected pairs cannot be established or the links are broken many times. Related to the NRL, means and confidence intervals are depicted with red points and red vertical intervals, respectively. NRL is high in terms of mean value because the number of routing packets increases. However, the dispersion is low because the pairs are selected based on the proposed methodology. Regarding the inter communications, the THR mean is also lesser and more scattered because there are pairs which can never establish communications. Similarly, the obtained NRL mean is lesser than when using the proposed methodology. That means that there are some pairs which never establish communication between them, and in consequence, the number of routing packets is low. For more details see Table 35.

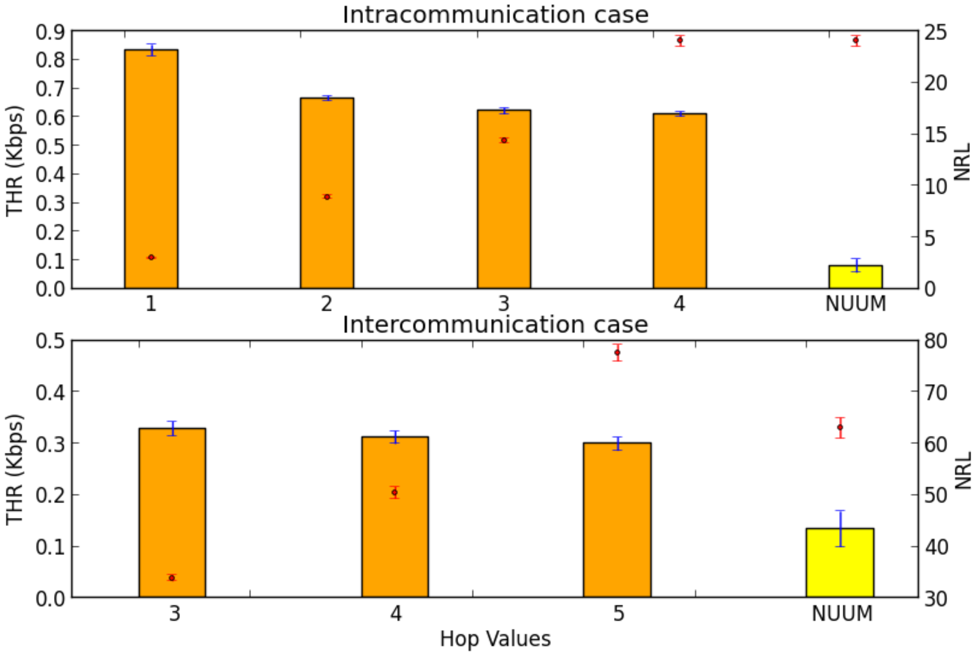

Figure 43 Throughput and NRL vs Number of hops

Intra Communication					
Hop Value	**1**	**2**	**3**	**4**	**NUUM**
THR (Kbps)					
Mean	0.8338	0.6666	0.6220	0.6111	0.0807
Confidence interval	0.0191	0.0084	0.0112	0.0085	0.0236
NRL					
Mean	2.9772	8.9015	14.390	24.064	25.148
Confidence interval	0.0550	0.1564	0.2434	0.5050	0.6523
Inter Communication					
Hop Value	**3**	**4**	**5**	**NUUM**	
THR (Kbps)					
Mean	0.3288	0.3119	0.2991	0.1335	
Confidence interval	0.0140	0.0125	0.0131	0.0346	
NRL					
Mean	33.8539	50.4297	77.5827	63.0468	
Confidence interval	0.5895	1.1534	1.6087	1.9991	

Table 35 THR and NRL vs Hop values in the scenario under test

6.2.2. Evaluation methodology for MANET broadcasting algorithms

The proposed methodology can also be applied to broadcasting communications. Broadcasting operation aims to maximize the reachability in the network. That is, the number of nodes that can be reached from a given source node. To achieve this goal, it is very useful to study and analyze the number of reachable nodes for each possible source node in a network. In simulation studies of MANET broadcasting algorithms, sources are selected randomly. It means that a set of sources nodes among all nodes in the network are selected to generate the broadcasting packets. Then, depending on the broadcasting algorithm, the nodes retransmit the packets throughout the network. The random selection can affect negatively the simulation results for different reasons. The main one is related to the scenario, as source nodes can differ in the number of reachable nodes. Even It could happen selecting source nodes with no reachable nodes (isolated nodes).

Furthermore, another aspect that can affect the simulation results is the distance to the reachable nodes in terms of number of hops. If the number of hops is high, it is more likely to lose some packets than in the case of a low number of hops. For instance, packets can be lost in intermediate node buffers or due to collisions with other packets. Consequently, the simulation results can drastically depending on the selected source nodes. To solve this problem we propose the selection of source nodes based on the reachability and the number of hops, which can be configured properly in the simulation set up.

6.2.2.1. Communication set up

Based on the previous chapter in which was proposed our framework, it is necessary to ensure that all broadcasting processes have started and all of them have finished during the measurement period. For that, we initiate the evaluation of the performance metrics after starting the first broadcasting process, and then finish the measurement period once the last process has finished. We avoid that there are not considered packets during the simulation. If we stop the measurement period earlier, some packets cannot reach all reachable nodes because some of them need more time in intermediate node buffers.

6.2.2.2. Number of simulations

As in the routing protocol case and based on the proposed methodology in section 5.1, the idea is to ensure good results in terms of mean and dispersion but do not waste more time than the necessary. In Figure 44 we depict the Re metric using and not using the proposed methodology, P.M., (orange and yellow bars respectively). We also depict the computing time (red and black points respectively). For this study, we use the same scenario that in previous sections (the scenario under test) and we select the sources based on the proposed methodology and random selection. Related to Re, we can see that the results are better in terms of mean value when not using the P.M. However, they are also too scattered because there are some sources which have a high Re but there are other which have a low Re. For this reason, the dispersion is also high (green vertical interval in Figure 44). However, if we focus on the case in which we use the P.M., the computing time is lower and the results are lesser scattered (blue vertical interval in Figure 44) due to the fact that these sources are selected based on the same properties.

Consequently, using the P.M. we can obtain more reliable simulation results with a lower number of simulations (see Figure 44). From now on, we consider 5 sources as the best option because the results are not scattered and the computing time necessary to obtain them is quite low.

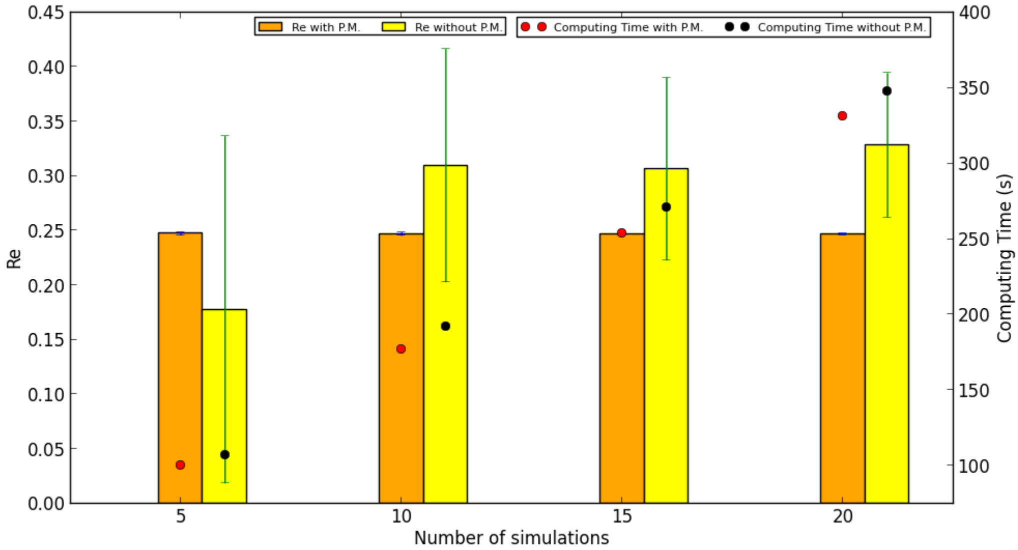

Figure 44 Re and computing time vs Number of simulations

With P.M.				
Number of simulations	5	10	15	20
Re				
Mean	0.2472	0.2468	0.2466	0.2467
Confidence Interval	0.0015	0.0015	0.0011	0.0095
Computing time (s)				
	100.25	177.36	254.16	331.58
Without P.M.				
Re				
Mean	0.1776	0.3095	0.3064	0.3283
Confidence Interval	0.1591	0.1068	0.0838	0.0661
Computing Time (s)				
	107.98	192.14	271.69	348.79

Table 36 Statistics measures for THR vs number of simulations

6.2.2.3. Source node selection

The selection mechanism proposed in this section avoids the random selection of the sources among all available nodes in the network. The random source node selection can make the simulation results vary for the following reasons. First, we can not guarantee that all source nodes have similar properties in terms of number of hops and reachable nodes. Related to the number of reachable nodes, the worst case corresponds to source nodes which do not have any reachable node or source nodes can have different number of reachable nodes. Both situations affect negatively the simulation results. To solve this situation we propose a new metric, which helps us to select source nodes based on the number of reachable nodes. We name this metric as partition degree (PD). We define the partition degree as the ratio of nodes (percentage) that are reachable from the source node through a multi-hop path. Notice that this metric is similar to the APA metric defined for the routing protocols. However, in broadcasting operation we do not have a destination node. Instead, we should analyze the number of nodes that can be reached from a given source node.

Another aspect that we should take in to account is the distance in terms of number of hops between the source nodes and the rest of reachable nodes. If the separation is high, the probability of losing packets for some reason is higher than for small separations. This is known as the die out problem in broadcasting operation. There are nodes that occupy central positions in the network so they have the rest of the nodes at a lower distance. Conversely, nodes located at the periphery of the network will have to pass their packets through a high number of intermediate nodes to reach the other extreme of the network. Therefore, it is clear that the position of the source node in the network is an important parameter to be considered for the source node selection.

We propose to use a new network metric named Average hop to reach the reachable nodes (AHRN) to take into consideration the position of the selected source nodes in the network. This metric is measured as the average distance, in terms of number of hops, from each source node to all their reachable nodes. To measure this metric we consider that all nodes can be source nodes. Based on this concept, we measure the number of hops from each source node to all reachable nodes and finally we calculate the mean value.

Based on these new metrics, PD and AHRN, we propose a selection mechanism to select source nodes. This mechanism should guarantee that there are enough source nodes that meet the restrictions in terms of PD and AHRN. The first step is to measure the partition degree (for each node) and select the source nodes according to the PDs found in the network. The idea is that if we select all the sources with the same or similar PDs, the dispersion of the results will much lower leading toa lower number of simulations to obtain reliable results. It is important to point out that we have to choose a target PD value which ensures a minimum number of source nodes. This means that the selected PD should be representative among all the PDs that can be found in the network topology. The same strategy is necessary to select the source nodes based on the average hops to reach the reachable nodes. That is to select a target AHRN that ensures a minimum number of source nodes. Next, we show how to apply the proposed methodology in disaster scenarios (scenario under test). The procedure is as follows: First, we obtain the distribution of the PD and AHRN metrics for all the possible source nodes in the network. Then, we select the most representative values for both metrics. Finally, we benchmark the performance of flooding algorithm (baseline broadcasting algorithm) to show the importance of both metrics in the performance of broadcasting algorithms.

6.2.2.3.1. Partition degree distribution

First, we have to obtain the partition degree distribution in the scenario under test in order to select the target PD. For this study, we do not distinguish between intra and inter communications. Due to the big dimensions of the scenario, it is expectable that the most of possible sources will have a low PD value. According to Figure 45, the maximum PD obtained is 0.55. This means that only 55 % of nodes are reachable in the best case.

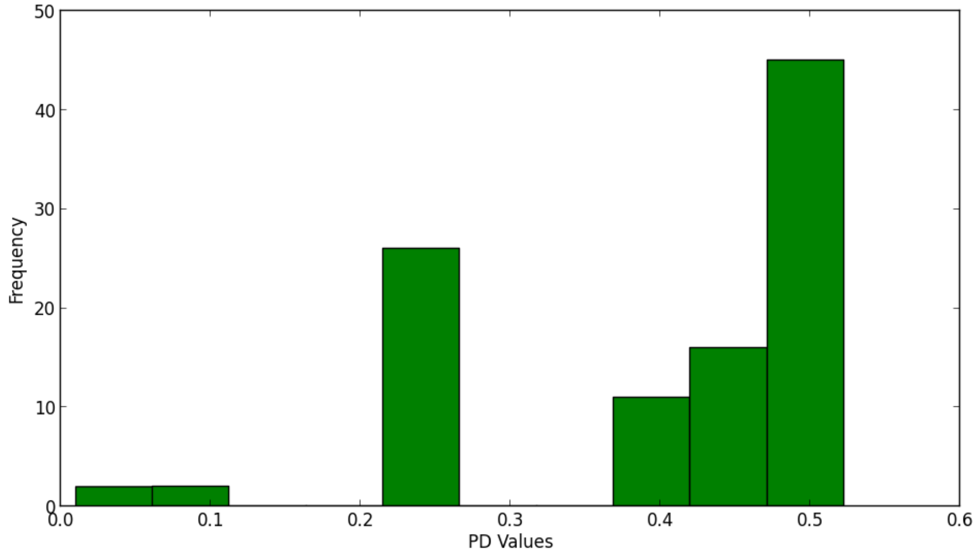

Figure 45 PD distribution

As we can see in Figure 45, most of the PD values are close to 0.5. This means that on average each node has around 50 reachable nodes. Therefore, a PD of 0.5 is a representative value of the PD of the network. Nevertheless, there are some nodes which have a low number of reachable nodes. This situation corresponds to nodes which are more isolated. Related to the target PD, we have to ensure a high number of source nodes with this value and we also are interested in the highest one because we want to reach the maximum number of nodes. Therefore, we select the target PD as 0.5. We have around 45 source nodes which are close to the target PD value (see Figure 45).

6.2.2.3.2. Average hops to reach the reachable nodes distribution

After the selection of sources based on PD (PD=0.5), the next step in the proposed procedure is to select sources based on AHRN. Again, we obtain the AHRN distribution in the scenario under test (see Figure 46). Then, we should choose a representative target AHRN which ensures that the reachable nodes are separated by the same number of nodes.

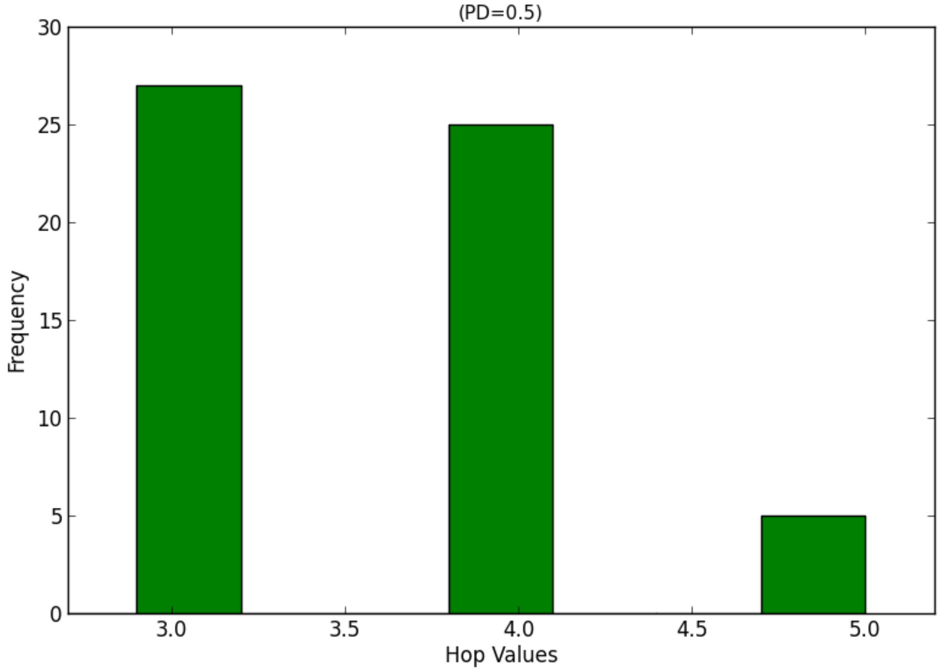

Figure 46 AHRN Distribution

As we can see in Figure 46, 5 hops is a representative value that guarantees a suitable evaluation of the broadcasting algorithms. Table 37 shows a summary of the source node selection .

Target PD	Target AHRN
0.5	5

Table 37 Source node selection summary

6.2.2.4. Benchmarking the methodology with flooding algorithm

In this subsection we use flooding as a baseline broadcasting algorithm to benchmark the proposed methodology. We evaluate flooding using the proposed metric, PD and AHRN, respectively. To evaluate the proposed methodology we use the Re metric. In Figure 47 we depict Re for different values of PD to show the importance of the PD. For this study we select representative PD values (see Figure 45). We can see in Figure 47 that as the PD value increases the number of packets that reach the destination is higher. Therefore, there are big differences in the performance of flooding algorithm depending on the PD selected. We illustrate this situation with an example. If we select two sources randomly, their PDs could be 0.25 and 0.5 respectively (see Figure 47). For these PD values the obtained Re metric values are 0.25 and 0.36 (see Table 38) approximately. The resulting Re mean for both values is 0.3 and the confidence interval is 0.3069. The obtained confidence interval is quite high. However, when applying the proposed methodology, it guarantees that the obtained Re values are closer to the PD value selected. This situation illustrates that different values of PD mean that the network conditions are different for each case. Therefore, it is important to evaluate the broadcasting algorithms under the same network conditions. If we guarantee similar network conditions, we will achieve less disperse results (Figure 47).

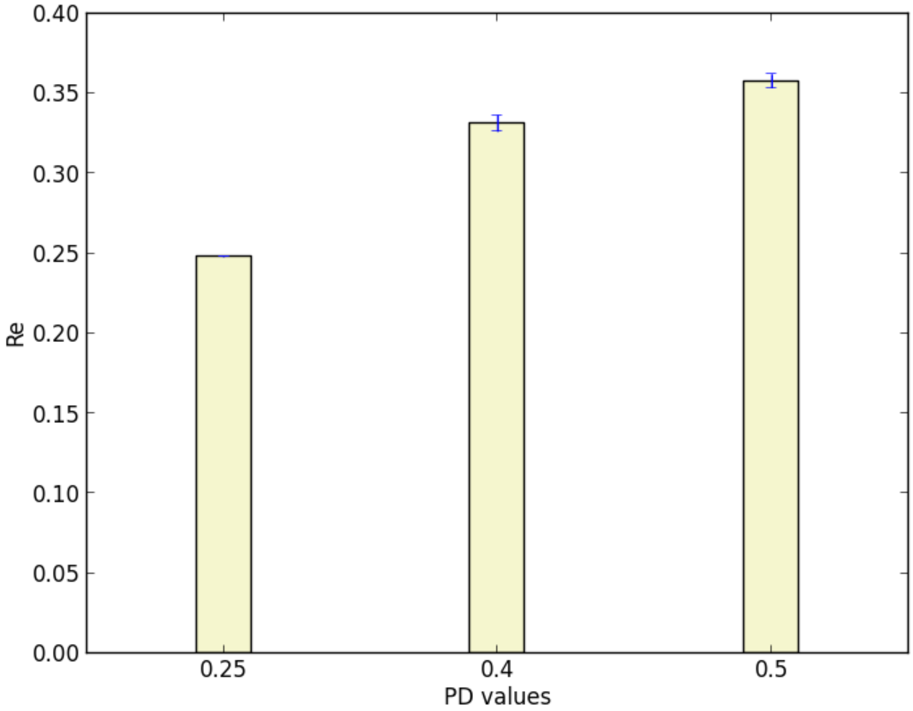

Figure 47 Re vs PD

PD value	**0.25**	**0.4**	**0.5**
Re			
Mean	0.2479	0.3312	0.3576
Confidence interval	0.0003	0.0052	0.0044

Table 38 Re vs PD values in the scenario under test

Now we also demonstrate that it is also important to select source nodes based on AHRN. For that we depict Figure 48 in which we show the obtained Re metric values for each value of number of hops. In Figure 48 we can see that the results are not scattered, it means that the selected sources have the same properties in terms of network conditions.

Let us illustrate with an example the importance of selecting the source nodes based on AHRN metric. If we select sources randomly, they could have AHRN metric values equal to 3 and 5 respectively. Consequently their Re values will be 0.25 and 0.46 approximately (see Table 39), with a mean value of 0.35 and a confidence interval of 0.3527, which is high compared with the mean value.

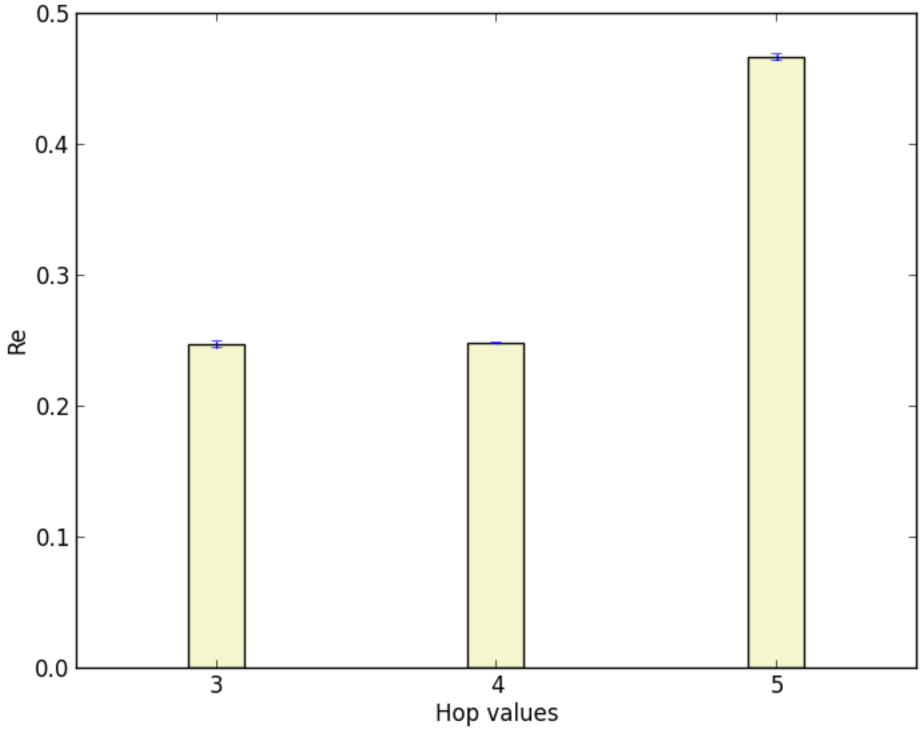

Figure 48 Re vs AHRN

Hop value	3	4	5
Re			
Mean	0.2468	0.2479	0.4665
Confidence interval	0.0009	0.0005	0.0024

Table 39 Re vs AHRN values in the scenario under test

6.3. Validation of the proposed methodology: A comparison of communication protocols in disaster scenarios

This section is focused on validating the proposed methodology using the disaster area mobility model and realistic conditions. The idea is to compare a high number of communication protocols (routing and broadcasting) in a disaster scenario. First, we detail the simulation environment used to conduct the simulation study. Then, we evaluate some widely used routing and broadcasting algorithms for MANETs.

6.3.1. Simulation environment

For the evaluation, we use NS-2.34 [14] under Debian Linux operating system. To simulate disaster mobility, we use the disaster area mobility model included in Bonnmotion [8]. Table 40 summarizes the general simulation settings used. Regarding the propagation model, we use the two-ray ground [15] reflection model because it gives more accurate prediction for long distances than the free space model.

Parameter	**Value**
Simulation Time	300s
Warm up period	50s
Routing Protocols	AODV,DYMO, LAR
Broadcasting protocols	Persistence, Irresponsible, Polynomial, Gossip and Flooding
Transmission range	500m
Number of Nodes	102
Transport protocol	UDP
Traffic Types	CBR
Maximum Packet in Queue	50
Packet Size (Application)	512 bytes (routing) 1000 bytes (Broadcasting)
Packet routing Rate	1 packet/s
Number of broadcast packets	60 Packets
Area Size	4000*4000 m^2
Mobility model	Disaster Area
Propagation model	Two-ray ground

Table 40 Simulation parameters

Regarding the disaster scenario used for the validation and evaluation, we use an imaginary simulation scenario which is composed of one incident location, one patient waiting for treatment area, two casualty clearing stations, one ambulance parking area, and one technical operation area. Table 41 includes more details about the features of the technical areas.

Parameter	**Values**
Total number of nodes	102
Total area	4000 x 4000 m
Nº Incident sites *(IL)*	1, with 30 transport units (mobile nodes)
Nº Patient waiting for treatment areas *(PWFTA)*	1, with 8 transport units and 2 static nodes
Nº Casualties clearing areas (CCS_n)	2, with 15 units transport each station
Nº Ambulances parking point *(APP)*	1, with 25 units transport, and 5 static nodes
Nº Technical operational command *(TEL)*	1, with 2 static nodes

Table 41 Features of the scenario

6.3.2. Reliable comparison of routing protocols in disaster scenarios

This part of our study is focused on presenting a fair and reliable comparison of MANET routing protocols in the disaster scenario under test. We depict these results with boxplot graphs and also we highlight with a green point the obtained mean of the samples. We divide the analysis into two parts intra communications and inter-communications.

6.3.2.1. Intra communications

Figure 49 shows the performance of used routing protocols for intra-communications. In general, the best results are achieved by AODV and LAR routing protocols. It can be easily seen that their mean values are better than those obtained by other routing protocols for the four metrics chosen for the evaluation. In terms of dispersion, we can observe that AODV is less scattered than LAR. For this reason, we select AODV as the best routing protocol for intra-communications. DYMO exhibits a high value of NRL that significantly affects the rest of performance metrics.

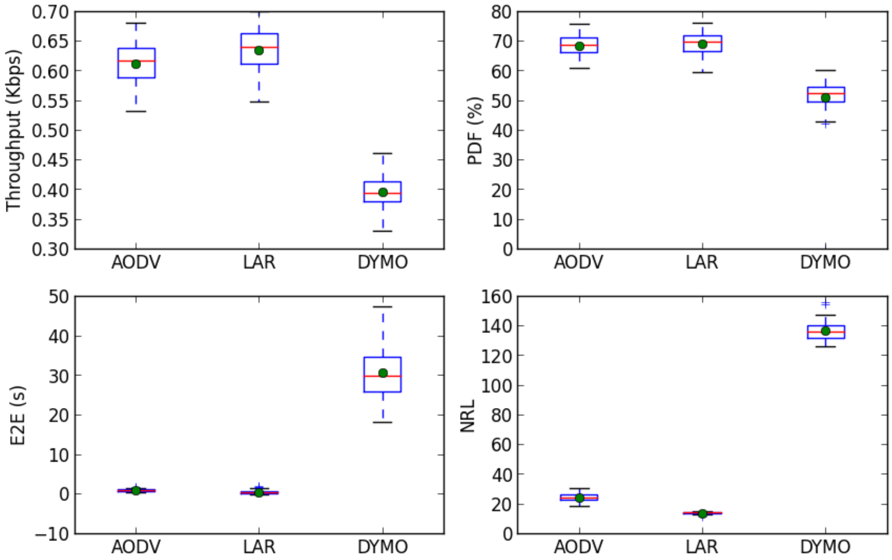

Figure 49 Used routing protocol simulation results. Intra Communications

6.3.2.2. Inter communications

In general, the performance of routing protocols worsens for in inter communications (see Figure 50). The main reason is that the APA values that can be obtained are low for inter-communications. Notice that the maximum throughput obtained is about 0.4, which is obtained by LAR routing protocol. This value is significantly lower than the maximum value obtained by LAR protocol for intra-communications, which is about 0.65. In general, LAR presents the best results again.

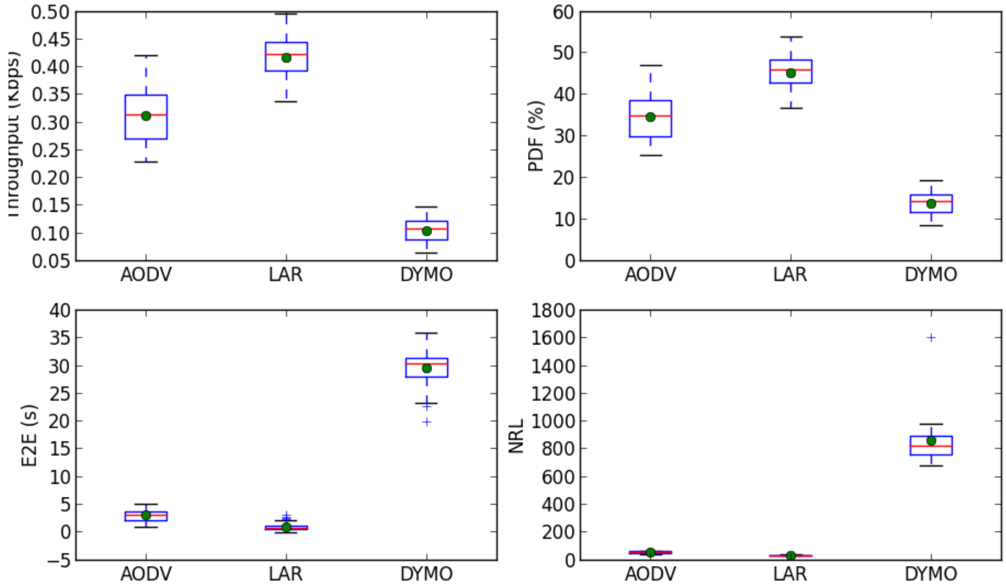

Figure 50 Used routing protocol simulation results. Inter Communications

6.3.3. Reliable comparison of broadcasting algorithms in disaster scenarios

In this subsection we focus on showing a comparison of probabilistic broadcasting algorithms in disaster scenarios using the proposed methodology. We compare probabilistic algorithms based on dissimilarity metrics and also well-known probabilistic broadcasting algorithms.

6.3.3.1. Comparison of broadcasting algorithms

We compare up to five different probabilistic broadcasting algorithms. P-persistence based on the Euclidean distance, flooding, Gossip based on fixed probabilities and p-persistence, polynomial and irresponsible based on dissimilarity metrics. To select the best dissimilarity metric, we focus on the study proposed in [16]. In this study, the Kulczynsky dissimilarity metric is selected as the best one among other dissimilarity metrics because it presents the best balance between Re and Be.

For this comparison we use the scenario proposed in previous sections (the scenario under test), and the sources are selected based on the proposed methodology. Specially, we use the features described in Table 37.

Figure 51 shows the performance of the selected probabilistic broadcasting algorithms using Kulczynsky dissimilarity metric, p-persistence based on the Euclidean distance, flooding and Gossip based on fixed probabilities. The best result in terms of Re is obtained by flooding and Gossip (p=0.8). However, the number of retransmitted packets is high. Consequently, the broadcast efficiency (Be in Figure 51) is low. If we want to reach many nodes and it is not important the congestion of the network, we will be interested in these broadcasting algorithms. However, if we need to find a balance between Re and the number of retransmitted packets, we should focus on the Be. As we can see in Figure 51, the best Be is obtained by Polynomial and Irresponsible broadcasting algorithms using Kulczynski dissimilarity metric.

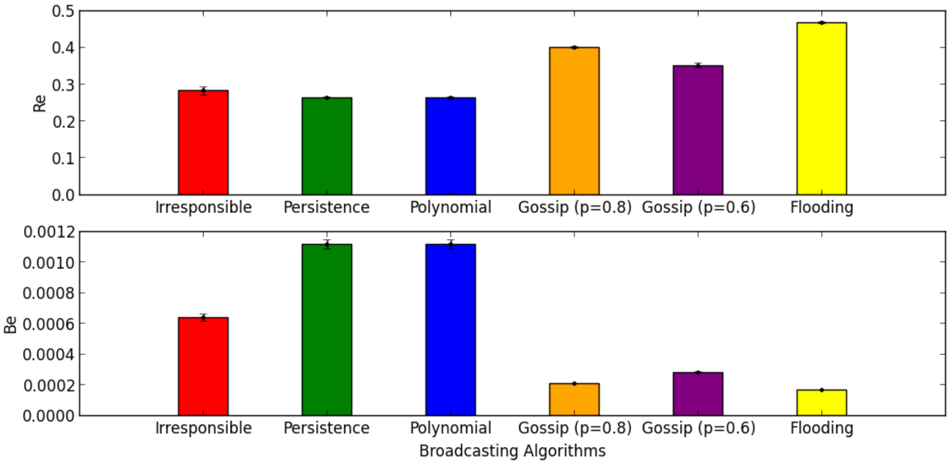

Figure 51 Comparison of the broadcasting algorithms based on Kulczynsky dissimilarity metric

6.3.4. Discussion of simulation results

This subsection aims to summarize the obtained simulation results in previous sections which were obtained based on the methodologies described in this book chapter. For that, we also divide this one into two categories. On the one hand, among the routing simulation results, AODV presents the best behaviour in terms of delivery packets, throughput metric, and end to end delay. However, LAR routing protocol achieves better results in terms of number of routing packets, NRL metric. It is due to the fact that LAR uses location information in its discovery phase. On the other hand, regarding the broadcasting algorithms, we compared five different algorithms and we concluded that the best one depends on our interest. If we want to reach the most number of reachable nodes we have to use flooding but with this selection the number of retransmitted packets is too high. For that, we have to focus on the Be metric. Consequently, Persistence and Irresponsible broadcasting algorithms present the best Be metric. Although some other previous studies have performed comparative studies of protocols for MANETs, this chapter goes one step further by applying a methodology to guarantee a fair comparison, reducing the influence of simulation conditions.

6.4. References

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7. CONCLUSIONS AND FUTURE WORKS

This section provides the main conclusions of this thesis, the future works that can derive from this thesis and a list of publications.

7.1. Conclusions

MANETs and VANETs communication protocols need to be evaluated before being tested in real scenarios. Simulation is the way to do that. However, obtaining reliable simulation, producing repeatable and representative simulation results or reducing the consumed time are not easy tasks. The reason is that there are many relevant configuration aspects that researchers have to take into account when they conduct their simulation studies. . We have proposed a methodology to conduct reliable simulations of communication protocols. Using this framework we are also able to reduce the time consumed by the network simulator to obtain the simulation results. Another advantage of our approach is that the obtained simulation results are reproducible by different researchers and the obtained results are the same. In addition to that, the proposed methodology can be extended to other scenarios o even multi-hop networks.

The proposed methodology includes aspects such as: i) measurement period to ensure that all the simulation measurements begin and end at the same time so as to improve the performance metric mean. ii) Source destination pair selection to avoid discrepancies in terms of path availability, and number of hops between the source and destination nodes to obtain results lesser scattered. iii) The number of trials to obtain reliable measurements to reduce the time consumed by the simulations. iv) Mobility models based on maps to emulate mobility of vehicles in urban scenarios. v) The importance of the repetition of source and destination so as not to congest certain nodes in the network. vi) Performance metrics and simulation analyses to evaluate routing protocols under different conditions. We have shown the importance of selecting these simulation parameters carefully in order to obtain reliable simulation statistics and make a fair and unbiased evaluation of communication protocols in two representative scenarios of multi-hop networks such as VANET and MANET disaster scenarios.

We have validated the proposed methodology in VANET scenarios by conducting a comparison of several well-known routing protocols with and without using the proposed methodology. The obtained simulation results demonstrate that the proposed methodology provides better results in terms of reliability (confidence intervals), and a smoother tendency of the performance metrics. For instance using the proposed methodology in this kind of scenarios, the number of delivered packets increases (about 55%) and also the confident intervals are better; they are reduced about 21%. In order to obtain these results, the computing time is also lower than in the case of not using the proposed methodology. This reduction is by half.

Furthermore, the obtained results applying the proposed methodology in the MANET disaster scenarios also corroborate the importance of improving the performance metric means and the dispersion of the simulation results. For this analysis, we also evaluated the same three routing protocols. In both cases, we analyse the importance of the APA and number of hops values. Also, using the proposed methodology in disaster scenarios, the obtained results in terms of performance metrics are better, both means and confidence intervals, and the consumed time to obtain those results are better, this one is also reduced by half.

We have extended the proposed methodology for the evaluation of MANET communication broadcasting algorithms in disaster scenarios. In this case, the topological properties of the scenario such as partition degree and separation in number of hops have been used to select the source nodes. We demonstrate that the source node selection has an important impact on the simulation results obtained. We validate this methodology in a realistic disaster scenario using the well-known disaster area mobility model. And we can conclude that with the proposed methodology, the confident intervals are reduced on average about 75%. And the computing time is lesser than in the case of not using the proposed methodology, about 8%.

7.2. Future works

Several promising future works can extend the results of this thesis. The first future work will be to develop a graphical application tool, which permits to the user select the main aspect that impact the simulation results and obtain the candidate communication pairs. This application will focus on the selection of source and destination nodes. The restrictions, the path availability and the distance in terms of number of hops, will be fixed and our application will return the candidate pairs. This tool will be open source so researchers could test their new communication algorithms correctly. The graphical application should also consider the mobility conditions, therefore, the mobility model will be also an input to be considered.

Another interesting future work is the extension of the proposed simulation methodology to other multi-hop ad hoc network like delay tolerant networks (DTN) simulations. In spite of these networks are not delay-sensitive, it is important for the nodes to be able to establish communication between them during the simulation time. It is even more important for nodes which have information to transmit. For this reason, it can be interesting to apply the proposed methodology to know what nodes could establish communication with other ones. The idea of this approach will be to detect how many encounters are possible between each node and detect if there are any node that never establishes communication with other ones. The idea is to provide a selection of sources nodes that guarantees a fair comparison among forwarding schemes in DTNs.

Another future work is the deployment of a mesh multi-hop network in the electronic engineering labs to apply in a real scenario the proposed methodology. The aim is to evaluate communication protocols, broadcasting or routing algorithms, both by simulation and in the proposed testbed. Based on the positions of the nodes in the real testbed, the proposed methodology can be applied to obtain the source and destination nodes which comply with the fixed restrictions in terms of number of hops and path availability. After that, a fair comparison among different communication protocols in a real scenario can be carried out. . The testbed will be based on Rasperry pi computers. The nodes will be equipped both with WiFi dongles and Bluetooth dongles. This testbed can be improved by including mobile nodes using smartphones to provide the network with the features of mobile network.

Finally and after a thorough analysis of the obtained results with the proposed framework, there are still some unexpected results yet. For instance, some obtained confidence intervals are still large. As future work, it is necessary to try to identify those factors which can cause the unexpected results. During our research work, we could identify that the congestion plays an important role in the simulation results. Of course, the congestion of the network will depend on the underlying application and it is not a configuration parameter. However, to guarantee a fair comparison of communication protocols, we should guarantee that the same application is considered for the evaluation of each communication protocol. Several topology factors can also affect the congestion of the network. For instance, the local density of a node like the number of neighbours per node is not taken into account when we apply the proposed selection of pairs based on the APA and number of hop metrics. The point that we want to highlight is that there is clear difference between the connectivity of the network from a theoretical point of view, as we have analysed with the APA and number of hops separation, and the real connectivity of the network that is also a function of the congestion of the network.

7.3. Publication list (Curriculum Vitae)

As a result of this thesis several publications have been derived. In particular, 3 papers have been published in journal with impact factor according to JCR, and one more is under review. Two chapters of book are being also reviewing for publications (with peer-reviewed guaranteed). Finally, 3 papers have been published in international conferences.

Papers in international journals:

1. J.M. García-Campos, J. Sánchez-García, D. G. Reina, S. L, Toral and F. Barrero. An evaluation

methodology for reliable simulation based studies of routing protocols in VANETs. Simulation Modelling Practice and Theory. Vol. 66, pp. 139-165. 2016.

2. J. Sánchez-García, J.M. García-Campos, D. G. Reina, S. L, Toral and F. Barrero. On-siteDriverID: A Secure Authentication Scheme based on Spanish eID Cards for Vehicular Ad Hoc Networks. En: Future Generation Computer Systems. Vol. 64, pp. 50-60. 2016.
3. J. Sánchez-García, J.M. García-Campos, D. G. Reina, S. L, Toral and F. Barrero. An Intelligent Strategy for Tactical Movements of UAVs in Disaster Scenarios. International journal of distributed sensor networks.Vol. 2016, pp. 1-20. 2016.
4. J. Sánchez-García, J.M. García-Campos, M. Arzamendia,D. G. Reina, S. L, Toral, D. Gregor and F. Barrero. .A survey on Simulation, Modelling and Practice of Unmanned Aerial and Aquatic Vehicles (UAAVs) Networks. Simulation Modelling Practice and Theory. *Under review*.

Book chapters:

1. J.M. García-Campos, D.G. Reina, J. Sánchez, S.L. Toral and F.Barrero. A Simulation Methodology for Conducting Unbiased and Reliable Evaluation of MANET Communication Protocols in Disaster Scenarios. Smart Technologies for Emergency Response and Disaster Management. *Under review*.
2. J. Sánchez-García, J.M. García-Campos, D. G. Reina, S. L, Toral and F. Barrero. Application of Nature Inspired Algorithms for Multi-hop Ad hoc Network Optimization Problems in Disaster Response Scenarios. *Under review.*

Papers in international conferences:

1. J.M. García-Campos, D.G. Reina, S.L. Toral, N. Bessis, F.Barrero, E. Asimakopoulou and R. Hill. Performance evaluation of reactive routing protocols for VANETs in urban scenarios following good simulation practices. Innovative mobile and internet services in ubiquitous computing (IMIS). Pp. 1-8. 2015.
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