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Contribution to design a communication framework for Vehicular Ad hoc Networks in urban scenarios

by

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A mis papás
por todo el apoyo y tanto amor...

"El valor de los sentimientos no depende del tiempo que duran, sino de la intensidad con que ocurren. Por eso hay momentos irrepetibles y personas inolvidables."

∼ *Fernando Pessoa*

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Abstract

The constant mobility of people and the growing need to be always connected make vehicular networks an area of main interest. The large number of vehicles that nowadays can be found in the roads and the advances in technology make Vehicular Ad hoc Networks (VANETs) be a major area of research.

Vehicular Ad hoc Networks are a special type of wireless Mobile Ad hoc Networks (MANETs), which allow a group of mobile nodes configure a temporary network and maintain it without the need of a fixed infrastructure. A vehicular network presents some specific characteristics, as the very high speed of nodes, i.e., vehicles. Due to this high speed the topology changes are frequent and the communication links may last only a few seconds. These networks have a wide area of application, being able to have communication between the nodes themselves (V2V) and between vehicles and a fixed infrastructure (V2I).

Among the main challenges in these networks is road safety where both governments and manufacturers have focused their main efforts. Thanks to the fast development of wireless communication technologies, researchers have achieved to introduce vehicular networks in daily communications enabling a wide diversity of services to offer.

Smart cities are now a reality and have a direct relationship with vehicular networks. With the help of existing infrastructure such as traffic lights, we propose a scheme to update and analyse traffic density and a warning system to spread alert messages. With this, traffic lights assist vehicular networks to take proper decisions. This would ensure less congested streets (which reduces pollution). It would also be possible that the routing protocol forwards data packets to vehicles on streets with enough neighbours to increase the possibility of delivering the packets to destination (minimizing loss of information).

Sharing updated, reliable and real-time information, about traffic conditions, weather or security alerts, increases the need of algorithms for the dissemination of information that take into account the main benefits and constraints of these networks. Also consider critical services that require a level of quality and service is another important challenge. For all this, routing protocols for vehicular networks have the difficult task to select and establish transmission links to send the data packets from source to destination through multiple nodes using intermediate vehicles efficiently.

The main objective of this thesis is to provide improvements in the communication framework for vehicular networks to improve decisions to select next hops in the moment to send information, in this way improving the exchange of information to provide suitable communication to minimize accidents, reduce congestion, optimize resources for emergencies, etc. Also, we include intelligence to vehicles at the moment to take routing decisions. Making them map-aware, being conscious of the presence of buildings and other obstacles in urban environments. Furthermore, our proposal considers the decision to store packets for a maximum time until finding other neighbouring nodes to forward the packets before discarding them.

For this, we propose a protocol that considers multiple metrics that we call MMMR (*A Multimetric, Map-aware Routing Protocol*). MMMR is a protocol based on geographical knowledge of the environment and vehicle location. The metrics considered are the distance, the density of vehicles in transmission range, the available bandwidth and the future trajectory of the neighbouring nodes. This allows us to have a complete view of the vehicular scenario to anticipate the driver about possible changes that may occur. Thus, a node can select a node among all its neighbours, which is the best option to increase the likelihood of successful packet delivery, minimizing time and offering a level of quality and service.

In the same way, being aware of the increase of information in wireless environments, we analyse the possibility of offering anonymity services. We include a mechanism of anonymity in routing protocols based on the *Crowd* algorithm, which uses the idea of hiding the original source of a packet. This allowed us to add some level of anonymity on VANET routing protocols.

The analytical modeling of the available bandwidth between nodes in a VANET, the use of city infrastructure in a smart way, the forwarding selection in data routing by vehicles and the provision of anonymity in communications, are issues that have been addressed in this PhD thesis. In our research work we provide contributions to improve the communication framework for Vehicular Ad hoc Networks obtaining benefits to enhance the everyday of the population.

Resumen

La movilidad constante de la personas y la creciente necesidad de estar conectados en todo momento ha hecho de las redes vehiculares un área cuyo interés ha ido en aumento. La gran cantidad de vehículos que hay en la actualidad, y los avances tecnológicos han hecho de las redes vehiculares (VANETS, Vehicular Ad hoc Networks) un gran campo de investigación.

Las redes vehiculares son un tipo especial de redes móviles ad hoc inalámbricas, las cuales, al igual que las redes MANET (Mobile Ad hoc Networks), permiten a un grupo de nodos móviles tanto configurar como mantener una red temporal por sí mismos sin la necesidad de una infraestructura fija. Las redes vehiculares presentan algunas características muy representativas, por ejemplo, la alta velocidad que pueden alcanzar los nodos, en este caso vehículos. Debido a esta alta velocidad la topología cambia frecuentemente y la duración de los enlaces de comunicación puede ser de unos pocos segundos. Estas redes tienen una amplia área de aplicación, pudiendo tener comunicación entre los mismos nodos (V2V) o entre los vehículos y una infraestructura fija (V2I).

Uno de los principales desafíos existentes en las VANET es la seguridad vial donde el gobierno y fabricantes de automóviles han centrado principalmente sus esfuerzos. Gracias a la rápida evolución de las tecnologías de comunicación inalámbrica los investigadores han logrado introducir las redes vehiculares dentro de las comunicaciones diarias permitiendo una amplia variedad de servicios para ofrecer.

Las ciudades inteligentes son ahora una realidad y tienen una relación directa con las redes vehiculares. Con la ayuda de la infraestructura existente, como semáforos, se propone un sistema de análisis de densidad de tráfico y mensajes de alerta. Con esto, los semáforos ayudan a la red vehicular en la toma de decisiones. Así se lograría disponer de calles menos congestionadas para hacer una circulación más fluida (lo cual disminuye la contaminación). Además, sería posible que el protocolo de encaminamiento de datos elija vehículos en calles con suficientes vecinos para incrementar la posibilidad de entregar los paquetes al destino (minimizando pérdidas de información).

El compartir información actualizada, confiable y en tiempo real sobre el estado del tráfico, clima o alertas de seguridad, aumenta la necesidad de algoritmos de difusión de la información que consideren los principales beneficios y restricciones de estas redes. Así mismo, considerar servicios críticos que necesiten un nivel de calidad y servicio es otro desafío importante. Por todo esto, un protocolo de encaminamiento para este tipo de redes tiene la difícil tarea de seleccionar y establecer enlaces de transmisión para enviar los datos desde el origen hacia el destino vía múltiples nodos utilizando vehículos intermedios de una manera eficiente.

El principal objetivo de esta tesis es ofrecer mejoras en los sistema de comunicación vehicular que mejoren la toma de decisiones en el momento de realizar el envío de la información, con lo cual se mejora el intercambio de información para poder ofrecer comunicación oportuna que minimice accidentes, reduzca atascos, optimice los recursos

destinados a emergencias, etc. Así mismo, incluimos más inteligencia a los coches en el momento de tomar decisiones de encaminamiento de paquetes. Haciéndolos conscientes de la presencia de edificios y otros obstáculos en los entornos urbanos. Así como tomar la decisión de guardar paquetes durante un tiempo máximo de modo que se encuentre otros nodos vecinos para encaminar paquetes de información antes de descartarlo.

Para esto, proponemos un protocolo basado en múltiples métricas (MMMR, *A Multimetric, Map-aware Routing Protocol*), que es un protocolo geográfico basado en el conocimiento del entorno y localización de los vehículos. Las métricas consideradas son la distancia, la densidad de vehículos en el área de transmisión, el ancho de banda disponible y la trayectoria futura de los nodos vecinos. Esto nos permite tener una visión completa del escenario vehicular y anticiparnos a los posibles cambios que puedan suceder. Así, un nodo podrá seleccionar aquel nodo entre todos sus vecinos posibles que sea la mejor opción para incrementar la posibilidad de entrega exitosa de paquetes, minimizando tiempos y ofreciendo un cierto nivel de calidad y servicio.

De la misma manera, conscientes del incremento de información que circula por medios inalámbricos, se analizó la posibilidad de servicios de anonimato. Incluimos pues un mecanismo de anonimato en protocolos de encaminamiento basado en el algoritmo *Crowd*, que se basa en la idea de ocultar la fuente original de un paquete. Esto nos permitió añadir cierto nivel de anonimato que pueden ofrecer los protocolos de encaminamiento.

El modelado analítico del ancho de banda disponible entre nodos de una VANET, el uso de la infraestructura de la ciudad de una manera inteligente, la adecuada toma de decisiones de encaminamiento de datos por parte de los vehículos y la disposición de anonimato en las comunicaciones, son problemas que han sido abordados en este trabajo de tesis doctoral que ofrece contribuciones a la mejora de las comunicaciones en redes vehiculares en entornos urbanos aportando beneficios en el desarrollo de la vida diaria de la población.

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Glossary

A-STAR	Anchor based Street and Traffic Aware Routing
ABE	Available Bandwidth Estimator
ACK	Acknowledgement
ANOVA	Analysis of Variance
AP	Access Point
BDAM	Building and Distance Attenuation Model
BER	Bit Error Rate
BM	Building Model
C2C-CC	Car-2-Car Communication Consortium
CBR	Constant Bit Rate
CCH	Control Channel
CEN	Comité Européen de Normalisation
CMGR	Connectivity-aware Minimum-delay Geographic Routing
CPU	Central Processing Unit
D-VADD	Direction First Probe-VADD
DAM	Distance Attenuation Model
DGT	Dirección General de Tráfico
DIFS	Distributed Inter-Frame Space
DIVA	Developing Next Generation Intelligent Vehicular Network and Applications
DSRC	Dedicated Short-Range Communications
ECC	Electronic Communications Committee
ENoLL	European Network of Living Labs
ETSI	European Telecommunications Standards Institute
EWMA	Exponential Weighted Moving Average

FIFO	First-In First-Out
GDF	Geographic Data Files
GloMoSim	Global Mobile Information System Simulator
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GPSR-L	Greedy Perimeter Stateless Routing with Lifetime
GPSR-MA	Greedy Perimeter Stateless Routing with Movement Awarness
GUI	Graphical User Interface
GW	Gateway
H-VADD	Hybrid Probe-VADD
HCS	Highway Capacity Software
ICT	Information and Communications Technologies
ID	Identity
IDM-IM	Intelligent Driving Model with Intersection Management
IDM-LC	Intelligent Driving Model with Lane Changing
IP	Internet Protocol Address
ITS	Intelligent Transportation System
IVC	Inter-Vehicular Communication
JS	Junction Sequence
L-VADD	Location First Probe-VADD
LOS	Line Of Sight
LS	Link Stability
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MMOR	Multi-Metric Opportunistic Routing
MOE	Measures Of Effectiveness
MOPR	Movement Prediction-based Routing
MOVE	MObility model generator for VEhicular networks
NCTUns	National Chiao Tung University Network Simulator

OPNET	Optimized Network Engineering Tools
PDA	Personal Digital Assistant
PDF	Probability Density Function
PER	Packet Error Rate
PHY	Physical layer
PPPP	Public-Private-People Partnerships
PRESERVE	Preparing Secure Vehicle-to-X Communication Systems
QoS	Quality of Service
RD	Route Discovery
RERR	Route Error message
RPGM	Reference Point Group Mobility
RPM	Radio Propagation Model
RREP	Route Reply message
RREQ	Route Request message
RSU	Road Side Unit
RTT	Round Trip Time
RWM	Random Waypoint Model
SCH	Service Channel
SM	Statistic Message
SMP	Shared-Memory symmetric Processor
STRAW	STreet RAndom Waypoint
SUMO	Simulation of Urban MObility
SWANS	Scalable Wireless Ad hoc Network Simulator
TIC	Traffic Information Centre
TraNS	Traffic and Network Simulation Environment
TRANSYT	Traffic Network Study Tool
TSIS-CORSIM	Traffic Software Integrated System-Corridor Simulation
UCLA	University of California Los Angeles
V-AODV	AODV routing protocol for VANETs
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VADD	Vehicular Assisted Data Delivery

VANET	Vehicular Ad hoc Network
Veins	Vehicles in Network Simulation
WAVE	Wireless Access for Vehicular Environments
WSM	Wave Short Message
WSN	Wireless Sensor Network

Chapter 1

Overview

1.1 Introduction

The growth of ad hoc wireless networks poses one of the most promising fields in wireless networking and telecommunications of the last decade. The research into this area has expanded tremendously to include many topics.

Since several years ago, mobile computing has enjoyed a huge rise in popularity. In the past, users wanted to have the network at their disposal for innumerable conveniences. Years ago we only could imagine the possibility to download a roadmap, a movie or any traffic information from our car. The quickly development of the technology in combination with sufficiently fast and inexpensive wireless communication links and cheap mobile computing devices, make this a reality for many people today.

Nevertheless, there still are many commercial applications that appear feasible in the near future. In the last 5 years with the advent of the automobile industry showing interest in the future of Vehicular Ad hoc Networks (VANETs) [1] [4] mainly for safety applications. Indeed, this is probably the biggest new commercial application of ad hoc networks with specific applications such as safe driving. The fact that it has allocated spectrum in the 5.9 GHz region to this new application indicates that this research area is destined to grow into a commercially viable technology.

We are witnessing an exponentially growing interest in this area, both from academia and automobile industry: with 60-100 embedded sensors and their corresponding microprocessors, current vehicles can be seen as really mobile computing platforms. They are highly mobile and they have a high amount of embedded computing power. Nowadays, the number of potential applications have quickly expanded since the advantage to warn the driver and the co-pilot of any event occurred in the road ahead, such as traffic jam, accidents, bad weather, etc. This way, the number of traffic accidents may decrease and many lives could be saved. Besides, a better selection of non-congested roads will help to reduce pollution. In addition, some other interesting services, such as infotainment, Internet access or video streaming, could be possible and available through infrastructure along the roadside. Vehicular technology seeks to have easier transportation in roads and highways, safer and more comfortable for passengers.

Vehicular Ad Hoc Networks can be considered as a subset of Mobile Ad hoc Networks (MANETs) [5] which have been studied extensively in the literature during the last decade. A large number of interesting applications for Intelligent Transportation Systems (ITS) [6] [7] have been motivating the development of VANETs. In these networks, vehicles are equipped with communication devices to provide two types of communications: the exchange of messages with other vehicles in Vehicle-to-Vehicle communications (V2Vs) and the exchange of messages with roadside network infrastructure in Vehicle-to-Infrastructure communications (V2Is).

These communications in a VANET allow the development of several applications [8], some of them are already possible in the newest vehicles:

- Vehicle collision warning systems: Provides information to drivers about the environment, warning them about accidents to avoid another crash.
- Security distance warning: Estimates accurately the distances between vehicles. The driver is warned when the minimum distance with another vehicle is overtaken.
- Cooperative Intersection Safety: Vehicles arriving at a road intersection exchange messages to make a safe crossing. Important in blind crossing.
- Cooperative cruise control: Vehicles maintain the same speed cooperating among themselves in the exchange of information.
- Dissemination of road information: Informs the near and the distant vehicles about road flow, congestion, dangerous situations and also weather conditions.
- Internet access: Access local infrastructure network for infotainment services.
- Map location: Assists drivers in situations when they are lost in some point of the city.
- Automatic parking: A vehicle can park itself without the need of the driver's intervention.

1.2 Objective of this thesis

The main motivation of this thesis is to contribute in the development of vehicular communication technologies. We focus our work on vehicular networks in urban environments. The development of smart cities opens a new type of interesting services. However, the design of routing protocols for urban scenarios poses challenging issues that we had to tackle.

In this thesis we aim at designing a framework to improve the interchange of information over vehicular ad hoc networks in urban scenarios. To achieve this goal, an efficient routing protocol specially designed for vehicular environments is needed. We have developed analytical models and algorithms to assist the routing scheme seeking to improve the performance of the VANET. We focus our effort on urban scenarios, since the design of the routing protocols has to cope with the presence of buildings, traffic lights, variable vehicles' density, among other features which makes it really challenging.

To achieve this general objective, we worked step by step. First, we tried to improve the general scheme of routing in VANETs. Our proposals are based on the geographic protocol GPSR (Greedy Perimeter Stateless Routing) as a starting point for the development of a good routing protocol for VANETs. We discarded any topology-based routing protocol, such as AODV (Ad hoc On-Demand Distance Vector,) because the establishment of a full path is not advisable in VANET scenarios due to the high mobility of the nodes. We further improved the hop-by-hop forwarding decision to choose the best next forwarding node. We included a map-aware capability so that each vehicle is aware of the presence of buildings around. Also, we included a mechanism to minimize packet losses using a buffer to store packets in case that no neighbour was around.

Then, we introduced anonymity in the vehicular communications, since nowadays there is a lot of confidential information in the network and not all information has to be shared. So, we wanted to provide VANET communications with a level of anonymity to protect the information that is important for each user. In our approach, we considered the tradeoff between anonymity and Quality of Service (QoS) so that we provide anonymity but also we guarantee a certain level of QoS.

Our research also incorporates QoS in the routing decisions, since multimedia services required a certain level of QoS. We have designed a routing protocol that considers several metrics, focusing on the decrease of packet losses in VANETs. This contribution seeks to improve the communications in VANETs, trying to maximize the number of packets delivered to their destination. We also included in our approach our first improvements done over GPSR, such as the buffer mechanism and the map-aware capability. We used the NCTUns simulator to carry out performance evaluations of our proposals. We designed urban environments that simulate several conditions in cities, such as congested and free roads, accidents and dense/sparse scenarios.

Also, we have worked on smart cities by designing a framework where vehicles use the infrastructure already deployed in cities (as traffic lights) in order to process information as vehicles' density and weather conditions. These information helps drivers to take better route decisions (avoiding congested roads and thus reducing pollution and trip time) and better data routing decisions (improving the delivery of packets to destination).

It is important to highlight that our proposals are based on hop-by-hop forwarding decisions to select the best forwarding node. Also, they are aware of the quick changes of topology present in urban scenarios.

1.3 Organization of this thesis

This thesis is organized in eight chapters. In Chapter 2 an overview of vehicular ad hoc networks is presented including the main characteristics and differences with other ad hoc networks. Also, a summary of the standard IEEE 802.11p is included, besides some projects in vehicular areas, radio propagations models, mobility models and generators of mobility models. Finally, we present the more relevant routing protocols for VANETs recently published in the literature.

Chapter 3 deals with our first proposal of a proper routing protocol for VANETs. The design and implementation of our proposal are explained. We take as base the GPSR routing protocol and we include a building-aware algorithm to consider the presence of buildings in cities. It also includes the use of a buffer to try to maximize the probability to delivery packets successively. Finally, we present the comparison of our protocol to other protocols in different urban scenarios.

An available bandwidth estimation (ABE) for VANETs is included in Chapter 4. Trying to offer a certain level of QoS in VANET communications, we adapt the ABE algorithm [9] to our VANET urban scenarios. We include our adaptation of the ABE algorithm in our proposals. Finally, a further improvement of ABE is presented.

In Chapter 5 a new routing protocol based on multi-metric decisions is proposed. We introduce a short explanation of each metric considered, the forwarding decision based on a global unique value and the inclusion of this approach in the NCTUns simulator. Then simulation results are shown, the comparison to other protocols and finally we evaluate the importance of each single metric depending on the scenario.

In Chapter 6 we release a proposal to provide anonymity in routing protocols for VANETs. We base our proposal in the *Crowds* algorithm [3], which is explained in this chapter. After that, we present Our proposal and our implementation in NCTUns. Also, we include the adaptation of our algorithm in some routing protocols to carry out an evaluation. Finally, the results of several scenarios are shown.

In Chapter 7 we introduce a brief example of the importance of VANET services in the novel idea of the smart cities. We present two contributions: the measure of the traffic density and the management of warning messages. We present the framework and the important role that vehicular networks play to improve the traffic management and to reduce road accidents. Simulation results are shown at the end of this chapter.

Finally, conclusions, publications generated from this thesis and some future work guidelines are exposed in Chapter 8.

Chapter 2

Vehicular Ad hoc Networks

In this chapter, a general vision of the Vehicular Ah hoc Networks (VANETs) is presented. Beginning with its definition, following with its applications, then the main mobility models used in VANETs, mobility model generators, network simulators and main routing protocols specially designed for VANETs.

2.1 Introduction

Nowadays, the huge amount of cars in transit has arisen a big interest in developing vehicular communication technologies. In this respect, several innovative and cost-effective mobile services and applications for traffic networks are under investigation, emerging as the basis of the so called Intelligent Transportation Systems (ITS) [6] [7].

ITS have become an attractive research field for many years. Among many technologies proposed for ITS, wireless vehicular communication, covering Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, aims to increase road safety and transport efficiency and provide ubiquitous wireless connectivity to the Internet. Taking into account the assistances from these different means of communication, drivers and pedestrians could quickly obtain useful and emergent traffic information about the roads at a low cost. For this reason, wireless vehicular communication has become a very important technology.

2.1.1 Mobile Ad hoc Networks (MANETs)

A MANET (Mobile Ad hoc Network) (Fig. 2.1) is a collection of wireless devices than can dynamically form a network with a very simple deployment capability. MANETs permit new applications which have not been able to emerge until now to offer solutions in multiple environments that have no infrastructure. These nodes can usually move in a random way and are capable of self-organize themselves arbitrarily, collaborating in

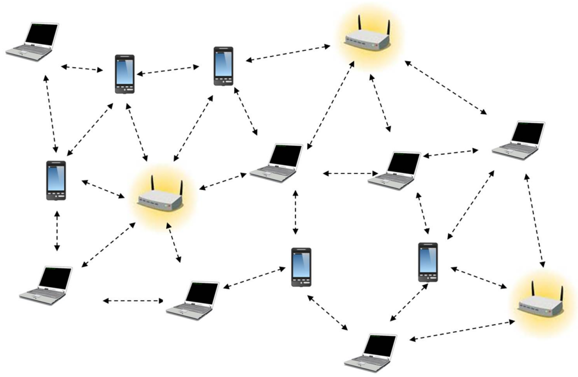


Figure 2.1: General scheme of a MANET.

order to communications succeed. Examples of such devices are laptops, PDAs, mobile phones and wearable computers.

The most outstanding features of MANETS are detailed below.

- *Dynamic network topology.* The dynamic network topology is certainly the element characterizing in MANETs. Since nodes are mobile, the network topology may change rapidly and unpredictably and the connectivity among the terminals may vary with time. MANETs should adapt to the traffic and propagation conditions as well as to the mobility patterns of the mobile nodes.

- *Autonomous terminals and self-organization.* In MANETs, each mobile terminal is an autonomous node, which may function as both a host and a router. Nodes are responsible for dynamically discovering other nodes to communicate or handle the network configuration, e.g. addressing and position location issues.

- *Distributed operation.* Since there is no background network for the central control of the network operations, the control management of the network is distributed among the nodes themselves. Nodes are involved in a MANET and should cooperate each other to implement the routing functions.

- *Multihop routing.* When it is necessary to deliver data packets from a source to a destination out of the direct wireless transmission range, packets should be forwarded via one or more intermediate nodes.

- *Fluctuating link-capacity.* The nature of high bit-error rates of wireless connections might be more critical in a MANET. The radio transmission rate is vulnerable to noise, fading, multiple access and interference conditions, and has less bandwidth than wired networks.

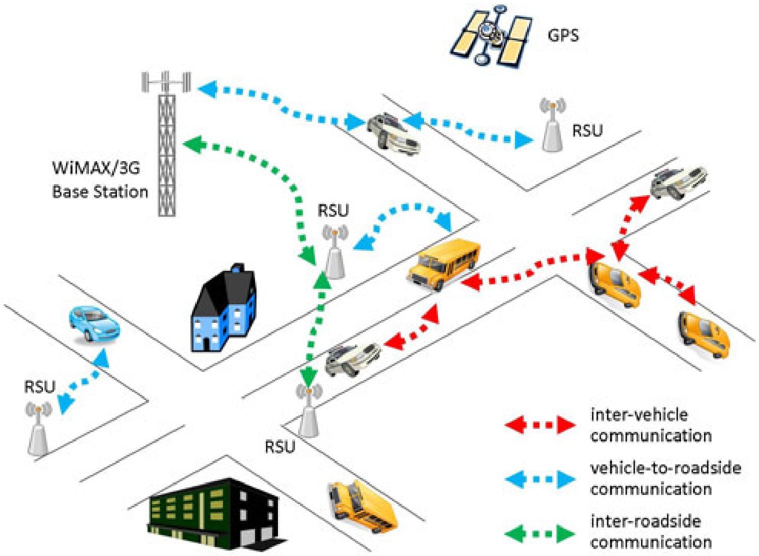


Figure 2.2: Example of a vehicular ad hoc network (taken from www.brunel.ac.uk).

- *Light-weight terminal.* In most cases, MANET nodes are mobile devices with limited processing capability, small memory size and low power storage. Such devices need optimized algorithms to execute computing and communicating functions.

2.1.2 Vehicular Ad hoc Networks (VANETs)

A Vehicular Ad hoc Network is a kind of MANET where nodes are vehicles. VANETs are wireless networks that emerged thanks to advances in wireless technologies and the automotive industry. Vehicular networks are formed by moving vehicles equipped with wireless interfaces. These networks are considered as one of the most promising ad hoc network for real-life applications, enabling communications among nearby vehicles as well as between vehicles and nearby fixed equipment (Road Side Unit, RSU). Vehicles can be either private, belonging to individuals or private companies, or public means of transport (e.g., buses and public service vehicles such as police cars). Fixed equipment can belong to the government or private network operators or service providers, see Fig. 2.2.

Vehicular ad hoc networks have special characteristics that distinguish them from other types of mobile ad hoc networks:

- *Unlimited transmission power*: The node (vehicle) itself can provide continuous power to computing and communication devices.

- *Higher computational capability*: Operating vehicles can afford significant computing, communication and sensing capabilities.

- *Predictable mobility*: Vehicles tend to have predictable movements that are usually limited to roadways. Roadway information is often available from positioning systems such as GPS (Global Positioning System) and map based technologies. Given the average speed, current speed and road trajectory, the future position of a vehicle could be easily predicted. Also, the hour of the day or the specific day of the week are determinant parameters to predict the vehicles' mobility.

- *Potentially large scale*: Vehicular networks can extend over the entire road network including many participants.

- *High mobility*: The environment in which vehicular networks operate is extremely dynamic and includes different configurations. The density of nodes and their speed can be very high, especially during rush hours or very low, i.e. during weekly nights.

- *Partitioned network*: Vehicular networks will be frequently partitioned. The dynamic nature of traffic may result in large inter-vehicle gaps in sparsely populated scenarios and therefore in several isolated clusters of nodes.

- *Network topology and connectivity*: Vehicular network scenarios are very different from classic ad hoc networks. Since vehicles are moving and changing their position constantly, scenarios are highly dynamic.

All these characteristics should be taken into account when designing a vehicular network.

2.1.2.1 The IEEE 802.11p standard for VANETs

Wireless Access for Vehicular Environments (WAVE) [10] is a set of standards and protocols whose goal is to facilitate the provision of wireless access in vehicular environments. It includes the **IEEE 802.11p** standard [10]. The primary goal was to develop public safety applications that can save lives and improve traffic flow, although other commercial services are also permitted. WAVE physical (PHY) and MAC (Medium Access Control) layers are based on IEEE 802.11a. However, some modifications are needed to improve the performance in VANET environments. Hence, the new standard IEEE 802.11p was designed to support:

- Longer ranges of operation (up to 1000 m).

- High speed vehicles (up to 500 km/h).

- Extreme multipath environments with many reflections with long delays (up to 5 μs).

- Overlapped ad hoc networks that need to operate with high quality of service.
- Nature of the automotive applications to be supported (e.g. reliable broadcast).

The philosophy of IEEE 802.11p is to make the minimum necessary changes to IEEE 802.11a so that WAVE devices can communicate effectively among fast moving vehicles in the roadway environment. The changes in the physical layer changes basically can be summarized in three parts:

- 10 MHz channel (half of the 802.11a) in order to have longer guard intervals and therefore, support higher delays. This could offer a best performance against multipath errors.
- Although there is a reserved bandwidth for WAVE purposes, there is still a high concern for cross channel interferences. IEEE 802.11p includes improvements in the receiver performance requirements in adjacent channel rejections.
- With the same aim, the channel spectrum masks defined in IEEE 802.11p are more stringent than the ones demanded by the current IEEE 802.11 radios.

The key parameters of the IEEE 802.11p, IEEE 802.11b and IEEE 802.11a standards are displayed in Table 2.1.

Table 2.1: Key parameters of the IEEE 802.11p, IEEE 802.11b and IEEE 802.11a standards.

	IEEE 802.11p	**IEEE 802.11b**	**IEEE 802.11a**
Bit rate	3-27 Mb/s	6-64 Mb/s	6-54 Mb/s
Communication range (outdoor)	$<$ 1000 m	$<$ 100 m	$<$ 100 m
Transmission power for mobile (max)	760 mW (US) 2W EIRP (EU)	100 mW	250 mW
Channel bandwidth	10 MHz 20 MHz	1-40 MHz	20 MHz
Allocated spectrum	75 MHz (US) 30 MHz (EU)	50MHz - 2.5 GHz 300 MHz - 5 GHz	40 - 20 MHz
Suitable for mobility	High	Low	Low
Frequency band(s)	5.86-5.92 GHz	5.4 GHz, 5.2 GHz	5 GHz
Standards	IEEE, ISO, ETSI	IEEE	IEEE

The Dedicated Short-Range Communications (DSRC) spectrum is structured into seven 10 MHz channels, see Fig. 2.3. The central one is the Control Channel (CCH) and is restricted to safety-critical communications only. The first and the last channel are reserved for special uses. The rest are Service Channels (SCH) available for both safety and non-safety usage and a 5MHz guard band. The allocation of dedicated

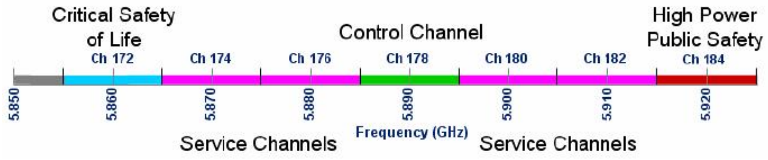


Figure 2.3: Distribution of Dedicated Short-Range Communications (DSRC) spectrum.

spectrum in Europe has been difficult due to the multiple parts involved. The Electronic Communications Committee (ECC) reserved in 2008 five channels of 10 MHz. These channels are placed in the frequency band between 5,875 and 5,925 GHz. This band is not exactly the same as in the US, however ECC recommends to use the spectrum between 5.855 - 5.875 GHz for non-secure ITS applications. Transmission power in this band is limited to 33 dBm.

2.1.2.2 Main applications of VANETs

The applications of VANET systems can be classified intro three primary directions: **transportation safety, traffic efficiency and infotainment**. The first two categories are the main two topics for the development of the vehicular technology, while the third one influences on the newly coined and existing services that naturally combine VANETs and ITS where they can act as a market force. Projects, standardization bodies, and consortia around the globe have been working on the design and development of applications for vehicular communications systems. Long lists of applications were initially compiled projecting into future technologies and looking into how vehicular communications can enhance support for drivers, road safety, passengers and traffic management.

The emerging vehicular networks will enable a variety of applications [11] above-mentioned:

- *Safety*: Vehicular network technologies will be applied to reduce accidents as well as to save lives and reduce injuries. A warning message will be broadcasted from a vehicle to its neighbourhood notifying about some event such as car collision or road surface conditions in order to decrease traffic accidents and enhance traffic flow control. It refers to applications or systems that increase the protection of the passengers in the vehicle as well as the vehicle itself.

- *Traffic Efficiency*: Vehicular network technologies will be applied to improve the traffic flow and to reduce congestion. Better efficiency results in less congestion and lower fuel consumption helping to minimize the environmental and economic impact.

- *Infotainment*: Services enhance the passengers' comfort and ability to perform personal and business transactions being in the vehicle combining information and entertainment and offering multimedia and Internet connectivity facilities for passengers.

2.2 Relevant research projects and commercial interests in VANETs

Nowadays several projects, consortiums and research groups focus mainly on safety (cooperative forward collision warning, pre-crash warning), traffic efficiency (enhanced route, optimal traffic lights) and infotainment (internet access in vehicles, point of interest notifications). In this section some of them are presented, highlighting their principal objectives.

2.2.1 Car-2-Car Communication Consortium

The Car-2-Car Communication Consortium (C2C-CC) [12] is a non-profit industrial driven organization initiated by European vehicle manufacturers and supported by equipment suppliers, research organizations and other partners. The C2C-CC is dedicated to the objective of further increasing road traffic safety and efficiency by means of cooperative Intelligent Transport Systems with Inter-Vehicle Communications supported by Vehicle-2-Roadside Communications. The C2C-CC supports the creation of a European standard for future communicating vehicles spanning all brands. As a key contributor the C2C-CC works in close cooperation with the European and international standardization organizations in particular European Telecommunications Standards Institute (ETSI) [13].

C2C-CC will be integrated in the refined telematics platform of the vehicles and its applications will mainly evolve three areas:

- Advanced driver assistance increasing road safety by reducing the number of accidents as well as reducing the impact in case of non-avoidable accidents.
- Increasing traffic efficiency with traffic congestion control resulting in reduced transport time, fuel consumption and thus contributing to protect the environment.
- User communications and information services offering comfort and business applications to driver and passengers

Some members of the C2C-CC are:

- *Partners*: Audi, BMW group, Honda, Renault, Volvo.
- *Associate Members*: Bosch, Hitachi, NEC, lesswire, ARADA systems.
- *Developer Members*: EUROCOM, INRIA (France), Universitat Ulm (Germany), University of Twente (Netherlands).

2.2.2 iCar Support

One of the goals of iCar Support [14] is to monitor ITS standardization initiatives. Part of iCar Support is the iMobility Forum [15]. The iMobility Forum succeeds the eSafety Forum [16]. The vision of this forum is to obtain safe, smart and clean mobility with zero accidents, zero delays, no negative impact on the environment and connected and informed citizens, where products and services are affordable and seamless, privacy is respected and security is provided. To work towards this vision, the forum provides a platform for all ITS stakeholders in Europe to discuss, define, coordinate and support activities to further innovation, research, development, deployment and use of ICT (Information and Communications Technologies) based transport systems and services.

The new Forum objectives cover the period from 2010 to 2020. In the time period 2011-2020, the iMobility Forum estimates for ITS the following potential contributions:

- 30% reduction in the number of fatalities across Europe.
- 30% reduction in the number of seriously injured persons across Europe.
- 15% reduction of road traffic related congestion.
- 20% improvements in energy-efficiency.
- 50% increase in availability of real time traffic and travel information.

2.2.3 Preparing Secure Vehicle-to-X Communication Systems

The goal of Preparing Secure Vehicle-to-X Communication Systems (PRESERVE, 2011-2014) [17], is to design, implement and test secure and privacy-protected V2X communication closer to reality by providing and field testing a security and privacy subsystem for V2X communications. PRESERVE will combine and extend results from earlier research projects, integrating and developing them to a pre-deployment stage by enhancing scalability, reducing the cost level, and addressing open deployment issues. It aims at providing comprehensive protection ranging from the vehicle sensors through the on-board network and V2V/V2I communication to the receiving application. As a result, PRESERVE will present a complete, scalable and cost-efficient V2X security subsystem that is close-to-market and will be provided to other projects and interested parties for ongoing testing.

Field operational testing will investigate a number of important scalability and feasibility issues. Further, the V2X security subsystem will also be provided to other projects to jointly investigate integration and performance in larger fleets of vehicles. Another strategic objective of PRESERVE is to contribute to on-going harmonization and standardization efforts at the European level.

The coordinator of the project is the University of Twente in Netherlands.

2.2.4 COMeSafety2

The COMeSafety2 project (2010-present) [18] aims at the coordination of the activities towards the realization of cooperative systems on European roads. The project will support and coordinate the development of the necessary standards under the ITS standardization mandate at ETSI and CEN (Comité Européen de Normalisation).

It will support the mutual validation and exploitation of programme results by active participation in task forces and organization of workshops. The project will push the finalization and implementation of the European ITS communications architecture, taking up from the COMeSafety support.

The project will provide a platform to bring together all the partners to agree on technical solutions and implement research results in a developing real world cooperative system environment. It will support the creation of open technical issues, explore new fields and develop further innovations. It will promote technical advances, standards and agreements on cooperative systems supporting the Intelligent Car Initiative and the Safety Forum.

2.2.5 eCoMove

The eCoMove project (2010-present) [19] will target three main causes of avoidable energy use by road transport to bring fuel wastage to a minimum:

- Inefficient route choice.
- Inefficient driving performance.
- Inefficient traffic management and control.

Tackling these inefficiencies means finding solutions to support them, as following:

- Apply the appropriate driving strategy in order to use the least possible fuel by finding the "greenest" route, the most economical use of vehicle functions, the best path through surrounding traffic and how to negotiate the next traffic signals with least chance of stopping.
- Fleet manager to adopt a self-learning "driver coaching system" based on incentives for energy efficiency gains, and a cooperative planning/routing system that selects the most economical route for deliveries.
- Traffic manager to optimize traffic lights phases and apply other traffic control measures so that the ensemble of vehicles in the network consumes the least possible energy, e.g., by granting priority to energy-greedy vehicles to avoid unnecessary stops.

2.2.6 DIVA

Developing Next Generation Intelligent Vehicular Network and Applications DIVA [20] is a research network with the goal to see developed and deployed distributed, robust, secure and fault-tolerant communication solutions that will enable the proliferation of intelligent vehicular network systems to reduce roadway fatalities, fossil-fuel consumption, greenhouse gas emissions and traffic congestions, while providing drivers and passengers with driving comfort applications such as location-aware services, multimedia streaming, local news, tourist information and alert messages on highways and city streets. The proposed technologies for intelligent vehicular networks will enable the development and testing of innovative products and services in order to reduce congestion, improve mobility over current practices and enhance safety for drivers and passengers. As a whole the DIVA network research proposes to cover several fundamental and practically relevant VANET aspects and issues. Although it is an ambitious project, that have assembled an experienced research team; industry partners and government representatives will collaborate to accomplish the proposed goal and objectives.

2.2.7 Summary of research projects in VANETs

As we see, there are several projects and consortiums with direct interest in research focus in vehicular networks. Mainly of the partners are universities and vehicles manufactures. The objectives of these projects are focus in issues related to V2V or V2I communications, as improve road safety, standardized end-to-end architecture for automotive telematics services, implementation of security requirements for vehicular communications, making vehicles smarter and safer, etc.

2.3 Radio propagation models

Due to the ad hoc nature of VANETs, no infrastructure is present. Due that is rely heavily on distributed measures to regulate access to the wireless channel. The correct function of a protocol once deployed in a real-world tested may differ greatly from the simulation results because can happened that the simulator may be overly optimistic. In some cases though, reality provides opportunities for two nodes to exchange information which would not have been possible in the simulator due to a simplistic propagation model.

The selection of a radio propagation model has a pronounced impact on the performance of a routing protocol because the propagation model determines the number of nodes in the collision range, an important input for contention and interference. At the same time, has a direct effect on a node's ability to transmit a packet to a neighbour node.

The mobility in VANETs also causes that the vehicles move in and out of each other's transmission range quickly and frequently. Depending on the propagation model a node may share a collision domain with few or hundreds of other nodes, because the model could consider the presence of buildings reducing the Line Of Sight (LOS) of the vehicles.

The propagation environment in the simulator is used to judge the effects of propagation of electro-magnetic waves through the medium, usually this medium is air.

The main Radio Propagation Models (RPMs) [21] [22] [23] [24] used are:

- *Free Space Model*: In the Free Space Model the received power depends only on the transmitted power, the antenna gain and the distance between the sender and the receiver. The main idea is that, as a radio wave travels away from an (omnidirectional) antenna, the power decreases with the square of the distance (see Equation (2.1)).

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^\alpha L} \tag{2.1}$$

  Where P_t is the transmitter power, G_t and G_r are the gains of the transmitter and receiver antennas and λ is the wavelength. α is the path loss exponent (equal to 2 in Free Space). L is the system loss. Often, G_t, G_r and L are set to one (matched antennas and no system loss).

  In a VANET vehicles move in cities where obstacles are the main concerns such as the buildings or other vehicles along the road that could block the transmission or communication. In this model obstacles are not taken into account.

- *Two Ray Ground Model*: This model is more accurate than the Free Space model because it considers a ground reflected propagation path between transmitter and receiver. The model is especially useful for predicting the received power at large distances from the transmitter, as it is shown in Equation (2.2).

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{2.2}$$

  Where h_t and h_r are the height of the transmit and receive antennas, respectively. Equation (2.2) shows a faster power loss than Equation (2.1) as distances increase.

- *Log-Normal Shadowing*: The Free Space model and the Two Ray Ground model predict the received power as a deterministic function of the distance. They both represent the communication range as an ideal circle. In reality, the received power at certain distance is a random variable due to multipath propagation effect, which is also known as fading effects. In fact, the above two models predict the mean received power at distance d. Instead, the Shadowing model uses a statistical approach to calculate the receiving power. It takes into account multipath propagation effects.

The shadowing model consists of two parts. The first one is known as path loss model, which also predicts the mean received power at distance d, denoted by $\overline{P_r(d)}$. It uses a closer distance to d_0 as a reference. $\overline{P_r(d)}$ is computed relatively to $P_r(d_0)$ as follows (see Equation (2.3)).

$$\frac{P_r(d_0)}{\overline{P_r(d)}} = \left(\frac{d}{d_0}\right)^{\beta} \tag{2.3}$$

β is called path loss exponent, and is usually empirically determined for field measurement. For example, β=2 for the Free Space propagation. Larger values correspond to more obstructions and hence a faster decrease in average in the received power as distance becomes larger. $P_r(d_0)$ can be computed from Equation (2.1). The path loss is usually measured in dB, given by Equation (2.4).

$$\left[\frac{\overline{P_r(d)}}{P_r(d_0)}\right]_{dB} = -10\beta log_{10}\left(\frac{d}{d_0}\right) \tag{2.4}$$

The second part of the shadowing model reflects the variation of the received power at certain distance. It is long-normal random variable, which is a Gaussian distribution if measured in dB. The overall shadowing model is represented by Equation (2.5).

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta log_{10}\left(\frac{d}{d_0} + X_{dB}\right) \tag{2.5}$$

Where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB}. σ_{dB} is usually called the shadowing deviation, and it is also obtained by measurement, with values from 4 to 12 in outdoor environments.

- *Rayleigh model*: The Rayleigh propagation model is a stochastic model used in situations when there is no LOS (Line of Sight), and only a multipath components exist. This model assumes that the magnitude of the received signal r varies randomly according to a Rayleigh distribution which is a sum of two uncorrelated Gaussian random variables $r(t) = \sqrt{I(t)^2 + Q(t)^2}$ using Equation (2.6).

$$p(r) = \frac{r}{\sigma^2} \exp\left(\frac{-r^2}{2\sigma^2}\right), \text{ for } r \geq 0 \tag{2.6}$$

Where σ^2 is the time average power of the received signal (the variance of $I(t)$ and $Q(t)$). This model is suitable for wireless channels that have no LOS component but multipath components that vary in amplitude and phase. The received components will have a zero mean and a uniformly distributed phase between $[0, 2\pi]$.

- *Ricean model*: Is a stochastic model for radio propagation anomaly caused by partial cancelation of a radio signal by itself; the signal arrives at the receiver by two different paths (hence exhibiting multipath interference), and at least one of the paths is changing (lengthening or shortening). Ricean fading occurs when one of the paths, typically a LOS signal, is much stronger than the others.

- *Nakagami model*: Is a mathematical general modeling of a radio channel with fading. Nakagami model has more configurable parameters. It is perfect to model the Free Space channel. The Nakagami distribution is defined by the following Probability Density Function (PDF) (Equation (2.7)).

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp\left[\frac{-mx^2}{\Omega}\right], \; x \geq 0, \Omega > 0, \; m \geq \frac{1}{2} \tag{2.7}$$

  The corresponding PDF of power at the given distance can be obtained by a substitution of variables and is given by a gamma distribution as shown in Equation (2.8).

$$P(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} \exp\left[-\frac{mx}{\Omega}\right], \; -x \geq 0 \tag{2.8}$$

  Where Ω is the expected value of the distribution and can be interpreted as the average received power. m is the called shape or fading parameter. The values of the parameter m and Ω are function of the distance. That is, the Nakagami model is defined by two functions: $\Omega(d)$ and $m(d)$.

  It is possible to conclude that Rayleigh distribution is a special case of Nakagami distribution where $m(d) = 1$ for every d, and that larger values of m causes less severe fading.

- *Building Models*: In addition to the previous radio propagation models, in [22] the authors proposed three new models that allow better modeling of losses due to attenuation and the presence of obstacles (closest to VANET urban scenarios). There are three proposals:

  – Distance Attenuation Model (DAM): Considers the signal attenuation due to the distance between the vehicles. To estimate the impact of signal attenuation on packet losses, it has two different possibilities: using a very detailed analytical model that relates signal strength and noise at the receiver with Bit Error Rate (BER) and Packet Error Rate (PER) or PER/Distance under specific channel conditions. The latter, through more restrictive, allows to simplify calculations and thus reduces simulation run-time.

  – Building Model (BM): Takes into consideration that buildings will absorb radio waves making communication only possible when the vehicles are in LOS. Fig. 2.4 shows an example of this model, where can notice that in a

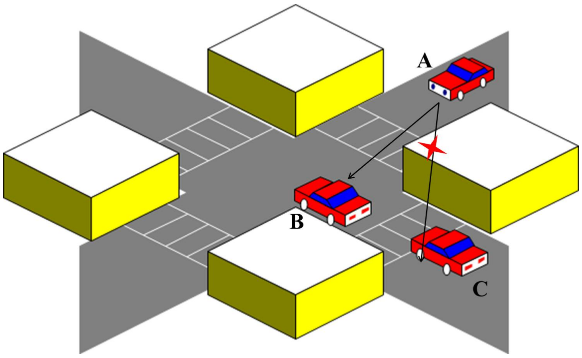


Figure 2.4: Building model example..

building model, only communication between vehicles A and B is possible. Vehicle C does not receive the message from vehicle A due to the presence of a building.

– Building and Distance Attenuation Model (BDAM): Combines both DAM and BM models. This model allows communication only when the received signal is strong enough and vehicles are in LOS. BDAM can be considered the most realistic model for urban scenarios.

2.3.1 Summary of radio propagation models

In this section we notice the importance of a correct selection of a radio propagation model in VANET communications. The radio propagation model has a strong influence in the performance of VANETs simulations.

In our environments the best choice are building models. Due that our tests are developed in urban environments best results are obtained when the vehicles considers the building presence and takes their decision based on that. These gives realism to our urban scenarios.

2.4 Mobility models for VANETs

Analysing the performance of a new proposal developed for VANETs in a real vehicular environment is difficult or even impossible. It is for that reason that researchers use simulators to carry out a performance evaluation under different scenarios and different network configurations. However, one should use a simulator as close to reality as possible to obtain reliable results, see appendix A.

Vehicular mobility models should provide moving patterns similar to the real behaviour of vehicular traffic so that we could trust the obtained simulation results. The most widely used mobility models are based on random models that cannot describe vehicular mobility in a realistic way because they do not take into account the particular human behaviour of the drivers neither the features of the road layout. Therefore, simulation results of the protocols under test may differ considerably from those that could be obtained by implementing the network in a real scenario.

According to [25], mobility models that are intended to generate realistic vehicular motion patterns should include the following aspects:

- *Accurate and realistic topological maps*: It is important to include several densities of intersections, multiple lanes, varying the kind of streets and use different speed limitations.
- *Obstacles*: Obstacles can be a restriction to the cars' movements and also they may block the wireless communications.
- *Attaction/repulsion points*: Attraction points are final destinations where drivers go (e.g. office or universities), and the repulsion points are the initial location (e.g. home). They also depends on the hour of the day.
- *Vehicles characteristics*: Realistic vehicular motion should take into consideration that a car or a truck has differences like acceleration, deceleration or speed as well as that some streets present some restriction depending on the kind of vehicle.
- *Trip motion*: This is the set of source and destination points in the scenario. Each driver has a different set depending on their interests.
- *Path motion*: A path is each road segment chosen by cars based on speed limitations, time of the day, road congestion, distance or even personal habits.
- *Smooth deceleration and acceleration*: Vehicles do not abruptly break and accelerate. Models for decelerations and accelerations should be considered.
- *Human driving patterns*: The mobility model should consider interaction with the environment such as the presence of another vehicles, overtaking, traffic jam or also pedestrians.
- *Intersection management*: Is the process of controlling an intersection, may be modeled static (stop signs), conditional (yield sign) or time-dependent (traffic lights).
- *Time patterns*: To consider the variable density during a day, which can alter the trip.
- *External influence*: Models the impact of accidents, temporary road works or real-time knowledge of the traffic status of the path.

The more characteristics a designer of mobility models follows, the more realistic it is going to be. These characteristics are the base of the different available approaches in vehicular mobility modeling.

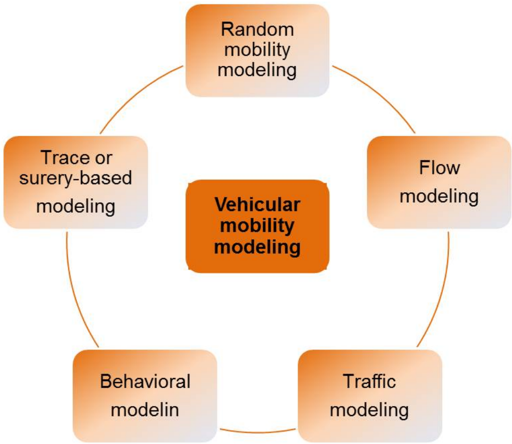


Figure 2.5: Classification of vehicular mobility modeling [1].

2.4.1 Classification of mobility models

Nowadays, it is essential to test and evaluate V2V or V2I networking proposals in real conditions. However, some limitations, such as high prices, city restrictions or technological limitations make simulations the best option in order to validate vehicular applications (as routing protocols), that is always the first step before that new technologies be used in the real-world. In vehicular environments, a main issue to take into account when the tests will be started, is define a realistic mobility patterns to obtain a simulation settings closer to reality.

In [1] it proposed a classification where mobility models are considered in five categories depending on their scopes and characteristics, see Fig. 2.5.

2.4.1.1 Random models

Random models are the more popular mobility models due to their simplicity. Given the vehicular environment, the graph is intended to represent a road topology, while the movement is random in sense that vehicles, individually or in groups, follow random paths over the graph, usually chosen aleatory speed. Some popular random models are:

- *Random Waypoint Model* (RWM), in this model, once that the destination is selected, each vehicle randomly selects points to follow in order to arrive to the destination. This behaviour is not common in real vehicular movements.

- *Reference Point Group Mobility* (RPGM) which defines a common direction for the group, and then adds some bounded randomness to the movement of the single vehicle within the group with respect to the common direction.

- In *Freeway* [26] the simulation area is a map that includes several freeways with no urban roads which means that no intersections are considered. Starting a simulation using this model, nodes are randomly distributed on the lanes, where vehicles' speed changes smoothly following a random acceleration. This model defines a minimum distance (for security reason) that two subsequent vehicles must maintain in a lane knowing that if the distance between two subsequent vehicles is less than the minimum, the backward vehicle should decelerate so that the forward vehicle can move away. No change of lanes is permitted. A vehicle starts from its initial randomly place until reaching the area limit and then the vehicle will be placed again randomly in another position and it will do the same again. Clearly, we can notice that this scenario is definitely unrealistic.

- *Manhattan* [26] simulates an urban environment. The first step in this model is to generate a map containing vertical and horizontal roads before the simulation begins. Each road contains two lanes, allowing the movement in the two directions (north/south for the vertical roads and east/west for the horizontal ones). As in the freeway model, vehicles in Manhattan are randomly placed on the roads and after that they move continuously according to history-based speeds, where the vehicles' speed changes smoothly following a random acceleration. When any vehicle reaches a crossroads, it can randomly choose a direction to follow: continuing straight forward, turning left or turning right leaving the probability of each decision to the authors. This model also follows the same strategy as in the freeway model to maintain a minimum distance between two subsequent vehicles for security reasons. However, in Manhattan model a vehicle has the possibility to change a lane at crossroads but without any control mechanism. This means that vehicles continue their movements without stopping at crossroads and this makes the model unrealistic too.

2.4.1.2 Flow models

A common classification is based on the level of details of the motion representation. Accordingly, mobility models can be divided in either macroscopic or microscopic [27].

- A *Macro-mobility model* focuses on the macroscopic aspects, i.e. road topology, initial and destination points, the journey through different points of the road, lane selection between the points, velocity of the vehicles in the different roads, number of lanes, overtaking and safety rules over each street of the used topology (traffic signs and traffic lights).

- A *Mesoscopic model* is described as an intermediate level of details between macro and micro mobility models. The main goal is obtain the benefits of both in a mixed model.

- A *Micro-mobility model* focuses on the microscopic aspects. It includes all aspects related to each vehicle behaviour, e.g., speed and acceleration. This is extremely linked to the driver's individual behaviour when the driver interacts with another driver or with the road infrastructure. That is, driving speed in different traffic conditions, acceleration, deceleration and overtaking criteria, conduct in presence of road intersections and traffic signs or traffic lights, time and day, driver's personal attitude which is directly related to driver's age, gender, mood, etc.

2.4.1.3 Traffic models

Traffic models [1] are able to model the public rules that have to follow the vehicle, some examples are the traffic lights, the stop signs, the turning policies or even model the full path of the vehicle. Besides, traffic models is divided in two clases: *trip* and *path*, that have a strong influence by the time. The trip model specify point to point the sequence that a vehicle have to follow from an origin to final destination. The path model, only define the full behaviour from the origin to destination. The influence of the time can be seen in the moment to start the movement of each vehicle, that can alters the full model and change the vehicle behaviour.

This model is somehow similar to the human behaviour, since these sequence points (origin-destination) are selected according to their needs, selecting the fastest path, the street with lower traffic , etc.

Trip planning generate a vehicle movement considering a origin to a destination. Each new direction could be selected at each crossroad, due to the destination could not be specified.

In the other way, path planning model the full path to be followed by each vehicle once that the origin and destination are set.

2.4.1.4 Behavioural models

The main restriction of mobility models is the challenge to predict the human reaction. A driver can not be programmed to react in a established way. A driver can be affected by the environment and distorting the traffic model.

Behaviour model [1] is based in the reaction of a human in front some stimulus in the streets. And to use this reactions as a vector to create a mobility model. This is a very challenge tasks due to each driver can react in a different way to the same stimulus that will produce a high computational cost of analysis.

Currently behavioural theory has increase the interest in the VANET research area, due to the relation between the vehicles movement and the human behaviour. A correct behaviour model can improve notoriously the safety applications, because could be possible anticipate the driver reaction in case of road accidents.

2.4.1.5 Trace-based models

Generate realistic vehicular mobility is a difficult task, only a few models are able to generate realistic motion patterns. Observing this, a new approach was followed, use mobility traces.

Some restrictions of this model are, the difficult to extrapolate a model that was obtained of public transport to the traffic of personal vehicles or the few availability of vehicular traces.

By using traces, various research teams have been able to extract mobility models that would reflect more realistically the pedestrian motion patterns we experience in real life. Synthetic models should accordingly be extended to show similar characteristics in order to be realistic.

Following a similar direction, if we could obtain an insight of the real distributions of speed, pause times, or inter-contact times in vehicular motion by using real traces, therefore we could accordingly configure the synthetic models.

2.4.1.6 Summary of mobility models

After the analysis of the mainly aspects to consider related to the mobility models that could be used in our simulations, we consider that the best way is to analyse each one of them and then decide the one that can make our environment closer to the reality. That means, from the random models classification we should use the Manhattan model because we are focusing on the study of a city environment. Also, our model must consider some of the traffic policies, i.e traffic lights, stops, be aware of the speed of the other vehicles, etc.

As a conclusion, our mobility model used is based on a Manhattan environment, where vehicles respect the presence of other vehicles as well as the distance and speed of the others and the presence of stop signs and the maximum speed established at the beginning of the simulations. All these characteristics used in our simulation environment makes it closer to a real urban scenario.

2.4.2 Mobility model generators for VANETs

Mobility model generators are used to generate travel paths of vehicles in a vehicular scenario. In most cases, the movement traces generated can be saved and imported into a network simulator to study the performance in VANET scenarios with the impact of specific movements. The performance in VANETs is very related with the connectivity that is determined by the movement traces. It is essential to generate realistic movement traces in order to obtain correct VANET protocol evaluations. In the following we summarize the main characteristics of some of the most used mobility simulators.

2.4.2.1 TSIS-CORSIM

Traffic Software Integrated System-Corridor Simulation (TSIS-CORSIM) [28] is a microscopic traffic simulation software package for signal systems, freeway systems, or combined signal and freeway systems. TSIS is an integrated development environment that enables users to conduct traffic operations analysis. CORSIM is the core simulation and modeling component of the Traffic Software Integrated System (TSIS) tool suite.

CORSIM program is a combination of two modules: NETSIM (to model surface streets) and FRESIM (to model freeways). It was developed by the University of Florida in 2010.

CORSIM is a stochastic simulation model, which means that it incorporates random processes to model driver, vehicle, and traffic system behaviours and interactions. Stochastic simulation models produce random outputs. Knowing that the output of a stochastic model is random, each run of a stochastic simulation model produces an estimation of a model's true characteristics for a particular set of input parameters. Thus, relying on the Measures Of Effectiveness (MOEs) generated from a single run of CORSIM may be misleading. To produce meaningful MOEs, several independent runs of the model will be required for each set of input parameters to be studied

Some capabilities included in TSIS-CORSIM 6.3 are: freeway and surface street interchanges, signal timing and signal coordination, emergency vehicles and signal pre-emption, freeway weaving sections, lane adds and lane drops, bus stations, bus routes, taxis. It is possible to add two-lane highways with passing and non-passing zones, as well as to include incident detection and management, simulation of right-hand drive or left-hand drive.

Also, it is possible to import files from Highway Capacity Software (HCS) [29] that includes streets, interchanges, freeways, ramps from Traffic Network Study Tool (TRANSYT-7F) [30] to generate a network with dozens of signalized intersections.

2.4.2.2 VISSIM

VISSIM [31] is a microscopic multi-modal traffic flow simulation software. It was developed by the PTV Group Transport in Germany. VISSIM presents the ability to simulate more than one type of traffic. Several types of traffic can interact mutually. In VISSIM the following types of traffic can be simulated: vehicles (cars, buses, and trucks), public transport (trams, buses), cyclists and pedestrians.

Interaction with VISSIM is done through a sophisticated graphical user interface (GUI). Users can perform 3D modeling and generate 3D animations. VISSIM requires Microsoft Windows.

2.4.2.3 S-PARAMICS

S-Paramics [32] is the latest version of the widely applicable Paramics microsimulation traffic flow modeling system, a software to design an analyse urban and highway networks.

S-Paramics simulates the individual components of traffic flow and congestion and presents its output as a real-time visual display for traffic management and road network design. S-Paramics represents the actions and interactions of individual vehicles as they travel through a road network. It models the detailed physical road layout, and includes features such as bus operations, traffic signal settings, driver behavioural characteristics and vehicle kinematics. As a consequence, S-Paramics can accurately portray the variable circumstances which lead to congestion in all types and sizes of road network.

S-Paramics models represent urban areas as diverse as Plymouth (England), Katowice (Poland), Glasgow (United Kingdom) and Amsterdam (Netherlands).

S-Paramics is being applied to trunk, urban, suburban and rural schemes for a very wide range of purposes and situations. It is being used routinely to examine signalized roundabouts, bus priority, emissions control, toll plaza design, urban traffic control, traffic calming, wide area traffic management, road works design, car park location and control, multi-level inter-changes, pedestrian and cyclist interaction, traffic impact, unusual/non-standard layouts and complex junctions, incident management, slow moving traffic on rural roads. Indeed every conceivable combination of circumstances which other modeling systems have difficulty simulating and analysing. It uses Microsoft Windows.

2.4.2.4 SUMO

SUMO (Simulation of Urban MObility) [33] is an open source, highly portable, microscopic road traffic simulation package designed to handle large road networks. Its main features include collision free vehicle movement, different vehicle types, single-vehicle routing, multi-lane streets with lane changing, junction-based right-of-way rules, hierarchy of junction types, an openGL graphical user interface (GUI), and dynamic routing. SUMO can manage large environments, i.e., 10000 streets. SUMO can import many network formats, such as Combining SUMO and OpenStreetMap [34]. Also, it is possible to simulate traffic in different locations of the globe.

2.4.2.5 MOVE

MOVE (MObility model generator for VEhicular networks) [35] is a realistic mobility model generator that uses SUMO [33] as compiler. Many realistic parameters are implemented in SUMO such as realistic accelerations, the usage of real maps with different types of roads with multiple lanes and traffic lights giving priorities to some vehicles. MOVE is composed of two components: the road map editor and the vehicle movement editor. The road map editor gives us the possibility to generate a road map manually and randomly or we can download real maps from TIGER/line files [36]. The vehicle movement editor allows us to choose some properties of vehicles like maximum speed, acceleration, probability of turning at crossroads, the path that should be taken. After that, the information of the two editors is sent to the SUMO compiler in order to generate a trace file in NS-2 [37] or Qualnet [38] format.

2.4.2.6 CanuMobiSim and VanetMobiSim

VanetMobiSim [27] is a CanuMobiSim [39] extension developed by the Institut Eurécom and the Politecnico di Torino which focuses on vehicular mobility with realistic automotive motion models at both macroscopic and microscopic levels. The framework includes a number of mobility models, as well as analysers for geographic data sources in various formats, and a visualization module. The set of extensions provided by

VanetMobiSim consists mainly of the two following: a vehicular spatial model and a set of vehicular-oriented mobility models.

Vehicular spatial model is composed of spatial elements (such as traffic lights or multi-lane roads), their attributes and the relationships link these spatial elements in order to describe vehicular areas. The spatial model is created from topological data obtained in four different ways: user-defined, random, Geographic Data Files (GDF) and based on the TIGER/line files from the US Census Bureau [36].

The main components of vehicular-oriented mobility models are the support of a microscopic level mobility models:

- Intelligent Driving Model with Intersection Management (IDM-IM), describing perfectly car-to-car and intersection managements.

- Intelligent Driving Model with Lane Changing (IDM-LC), an overtaking model is also included which interacts with IDM-IM to manage lanes changes and vehicle accelerations and decelerations.

VanetMobiSim as we can see, offers so many possibilities and features to create realistic scenarios. In addition, VanetMobiSim trace files can be imported into NS-2 [37], GloMoSim [40] or QualNet network simulators [38].

2.4.2.7 CityMob

CityMob [41] is a mobility pattern generator that allows researchers to easily create urban mobility scenarios including the possibility to model car accidents and to use a flooding based alert protocol to announce events. It is compatible with the NS-2 simulator [37] and it implements three different mobility models: Simple Model, Manhattan Model and Downtown Model.

Simple Model, models vertical and horizontal mobility patterns without direction changes. Traffic lights are not supported. *Manhattan Model* models cities as a Manhattan style grid with a uniform block size across the simulation area. All streets are two-way, with one lane in each direction. Car movements are constrained by these lanes. The direction of each node in every moment will be random, and it cannot be repeated in two consecutive movements. Moreover, this model simulates traffic lights at random positions (not only at crossroads), and with different delays. When a vehicle meets traffic lights, it will remain stopped until the traffic light turns to green. *Downtown Model* adds traffic density to the Manhattan model. In a real town, traffic is not uniformly distributed; there are zones with a higher vehicle density. These zones are usually in downtown, and vehicles must move more slowly than in the outskirts.

Regarding the mobility pattern generator CityMob, we have already developed a program in [42] to translate the output files (VANET scenarios) obtained with CityMob to be used in NCTUns. Thus, we are able to design realistic scenarios using vehicular mobility models in our NCTUns simulator.

Currently, Citymob v2 is available and it includes traffic lights at random positions (not only at crossings) and different delays, multiple lanes in both directions for every street, vehicle queues due to traffic jams, and the possibility of having more than one downtown zone.

2.4.2.8 Summary of mobility models generators

One of the most critical issues in VANET simulations is the mobility model generator because they are in charge of creating the movement of the vehicles during the simulation.

As we have seen in this section, there are several mobility generators but not all are compatibles with the network simulators. Also, each one offers different characteristics.

In this thesis, we selected CityMob because it offers a real movement of the vehicles. This mobility generator creates vehicle movements that follow streets in a city, respect the neighbour presence and generates stops in the crossings. It gives a real movement of each vehicle from an initial point to a destination during the simulation time. All these aspects are closely to the characteristics of the mobility models that we pretend to have in our simulations as we have explained in the previous section and due to that CityMob was chosen.

2.5 Routing protocols for VANETs

Future Intelligent Transportation Systems (ITS) require fast and reliable communication between cars (V2V) or between cars and a road side units (V2I). In ad hoc V2V communications where no supporting infrastructure is required, vehicles communicate when they are within the radio range of each other, or when multiple hop relay via other vehicles are available. Messages need to be routed from the source to one or several destinations. Desirable characteristics of a general routing protocols include:

- Minimal control overhead.
- Loop-free routing paths.
- Low complexity.
- Multicast capabilities.

Beside the above requirements, the vehicular environment poses new challenging requirements to V2V routing protocol design, including:

- Adapting routing information in highly mobile topologies.
- Short convergence time of the routing algorithms.
- Short delay for neighbour discovery.

- Scalability.

Compared to general wireless ad hoc networks, the roadway traffic environment in V2V communication consists of uncoordinated vehicles whose neighbouring vehicles constantly change and do not have relationships with each other [43]. As a result, the network topology in V2V communication changes very fast. Dynamic topology needs techniques to adapt routing information in highly mobile topologies.

Mobile Ad hoc Networks (MANET) protocols face several challenges when applied to vehicle networks. In MANETs, nodes usually move together as a group and have synchronous movement which ensures that the nodes have knowledge of each other. Although these protocols work well for coordinated nodes, it may not work well for vehicles on a highway where nodes are generally unknown and unrelated. For example, MANET protocols can incur high latencies in configuration an operation time with uncoordinated vehicles. As vehicle mobility increases, the available routes will change frequently which leads to even larger delay in routing algorithms operation.

Furthermore, the collision and contention of the underling MAC protocols such as IEEE 802.11 may increase routing convergence time and delay for neighbour discovery [43]. This is because many nodes within radio coverage tend to advertise their routing information at the same instant. In an ad hoc vehicle network environment where node density may be high, this is especially true.

Beside the above issues, scalability is also a challenging issue in routing protocol design in vehicle networks where the network can go from scarce to dense in a very short time. Parameters from other layers, such as wireless channel quality, power efficiency or application specific requirements may also affect the routing decisions and can be taken into account in the cross-layer design of routing protocols.

In recent years, some proposals of routing protocols which could be applied to VANETs have been developed. Below, we will present the most important routing protocols used, showing the main characteristics and its advantages and disadvantages.

2.5.1 Ad hoc On-demand Distance Vector (AODV)

Ad hoc On-demand Distance Vector (AODV) [5] [44] is a reactive protocol that uses the Bellman-Ford distance vector to operate in a mobile environment. It determines a route to a destination only when a node wants to send a packet. Routes are maintained as long as they are needed by the source and while there is connectivity between nodes in the path. Route discovery is based on query and reply cycles and route information is stored in all intermediate nodes along the route in the form of route table entries.

The following control packets are used: route request messages (RREQ) are broadcasted by nodes requiring routes to other nodes, route reply messages (RREP) are unicasted back to the source of RREQ, and route error messages (RERR) are sent to notify nodes of the loss of a link.

AODV implements a buffer to temporary store those packets for which the current node did not find a path. This buffer protects those packets instead of dropping them seeking to reduce losses. The buffer uses a first-in, first-out (FIFO) scheduler and its size was set to 30 packets. This protocol has been evaluated in different scenarios for VANETs [45] [46] [47] which have demonstrated that its performance is not suitable in high-mobility or low density scenarios due to its inherent end-to-end operation.

2.5.2 AODV routing protocol for VANETs (V-AODV)

V-AODV [48] is a version of Ad hoc On-demand Distance Vector (AODV) specially created for Vehicular Ad-hoc Networks (VANETs). This protocol was designed to use metric based on the radio link quality information (Bit Error Rate, BER) combined with delay information.

This protocol uses the hello messages to estimate the delay needed to reach each neighbour. The delay represent the Round Trip Time (RTT) between the source node of the hello message and the neighbour returning an acknowledgement (ACK). Then, it calculates a BER value between the two nodes and this value is included in a RREQ message. Every intermediate node tries to respond to the QoS requirement, only if there are enough resources to establish an optimal route.

The authors shows a improvement results in terms of packet losses and average end-to-end delay, but the evaluations was develop in a restricted scenario (10 nodes and 3 communications).

2.5.3 Greedy Perimeter Stateless Routing (GPSR)

Greedy Perimeter Stateless Routing (GPSR) [49], is a well-known geographical routing protocol and one of the first routing protocols especially designed for VANETs.

GPSR uses two algorithms to forward packets: *greedy forwarding*, which sends packets to the neighbour node closest to destination, this mode is used by default; and *perimeter forwarding*, which is used in case of greedy forwarding cannot be used. In perimeter mode, GPSR seeks to exploit the cycle-traversing properties of the right-hand rule to forward packets around voids where no closest neighbour is found.

This protocol in based in hop-by-hop decisions instead of end-to-end path establishment. That mean that take forwarding decisions in each hop.

The main drawback of GPSR is the use of outdated information to select the next forwarding node due to possible inconsistencies in the neighbour tables or in the destination node's location [47].

2.5.4 Anchor based Street and Traffic Aware Routing (A-STAR)

Anchor based Street and Traffic Aware Routing (A-STAR) [50] adopts the anchor-based routing approach with street awareness. The term "street awareness" is preferred over "spatial awareness" to describe more precisely the use of street map information in the routing scheme for anchor path computation. That is, using the street map to compute the sequence of junctions (anchors) through which a packet must pass to reach its destination. “Traffic” herein refers to vehicular traffic, including cars, buses, and other roadway vehicles. Also utilizes city bus routes as a help to find paths with high probability for delivering.

The A-STAR protocol consists of including information about the traffic density of the street edges weights. The main idea is to determine a sequence of streets with a high probability of having enough vehicles to do easy the transmission of the data.

The A-STAR algorithm uses anchor based unicast routing, which involves inserting a sequence of geographic forwarding points into a packet, through which the packet must travel on its route to destination. This protocol uses a static street map to route messages around potential radio obstacles. All these information is used to compute an anchor path using Dijkstra’s least weight path algorithm.

Packets are routed through alternative paths when routing has problems. Streets with problems are marked as out of service. The packet contains information about the recently discarded streets, and uses this information to choice a new route. This information is valid only during some time, since it can be outdated. In simulation study with other position based routing schemes, A-STAR demonstrates excellent improvement in packet delivery while maintaining reasonable end-to-end delay.

The main drawback of this protocol is the changes in the bus lines information, because this could be a negative effect in the routes decisions. Also, is not efficient in cities with unreliable traffic information.

2.5.5 Vehicular Assisted Data Delivery (VADD)

Vehicular Assisted Data Delivery (VADD) [2] is based on the idea of carrying and forwarding. The goal is to select a forwarding path with the smallest packet delivery delay. This protocol requires each vehicle to know its own position and also requires an external static street map that includes traffic statistics. Thus, VADD follows the following basic principles: a) Transmit through wireless channels as much as possible; b) If the packet has to be carried through certain roads, the road with higher speed (in the parsing vehicles) should be chosen and c) Due to the unpredictable nature of vehicular ad-hoc networks, we cannot expect the packet to be successfully routed along the pre-computed optimal path, so dynamic path selection should continuously be executed throughout the packet forwarding process.

Each packet has three modes: *Intersection, StraightWay and Destination*, as shown in Fig. 2.6, based on the location of the packet carrier. The most complex and complicated mode is the Intersection because of the many decisions that are made. In this mode the carrying vehicle must determine the next hop among all the availables to ensure that the packet will go through the correct direction.

Let us see an example based on Fig. 2.7: **A** has a packet to forward to certain destination. Assume the optimal direction for this packet is North. There are two available contacts for the packet carrier: **B** moving south and **C** moving north. A has two choices on selecting the next hop for the packet: **B** or **C**. Both choices aim

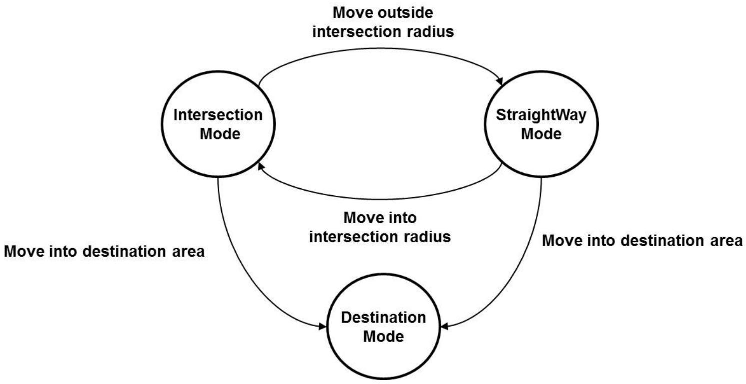


Figure 2.6: The transition modes in VADD [2].

at forwarding the packet towards North: selecting **B**, since **B** is geographically closer towards North and provides better possibility to exploit the wireless communication (e.g. **B** can immediately pass the packet to **D**, but **C** cannot) whereas selecting **C**, since **C** is moving in the packet forwarding direction. These two choices lead to two different forwarding protocols: Location First Probe (L-VADD) and Direction First Probe (D-VADD).

Where L-VADD tries to find the closest contact towards that direction as the next hop and D-VADD ensures that everyone agrees on the priority order and the vehicle moving towards the desired direction to forward the packet. With these ideas an Hybrid Probe (H-VADD) was also designed. H-VADD uses the shortest forwarding path in L-VADD when there is no routing loop, and uses D-VADD to address the routing loop problem of L-VADD. Among the proposed VADD protocols, the H-VADD protocol has much better performance.

This protocol in based in the use a several metrics as position and direction. Also include the carry and forwarding solution in sparse areas trying to increase packet delivery ratio and decrease end-to-end delay. Use several options of decisions in order to cover existing problem as low density and routing loops.

2.5.6 Connectivity-aware Minimum-delay Geographic Routing (CMGR)

Connectivity-aware Minimum-delay Geographic Routing [51] is a routing protocol for VANETs, which adapts well to the continuously changes that are present in these networks.

An effective routing protocol for vehicular networks should have good performance regardless of the status of the network. It is important to know that when the network is sparse the main challenge is to maximize the chance of reception before packet timeout,

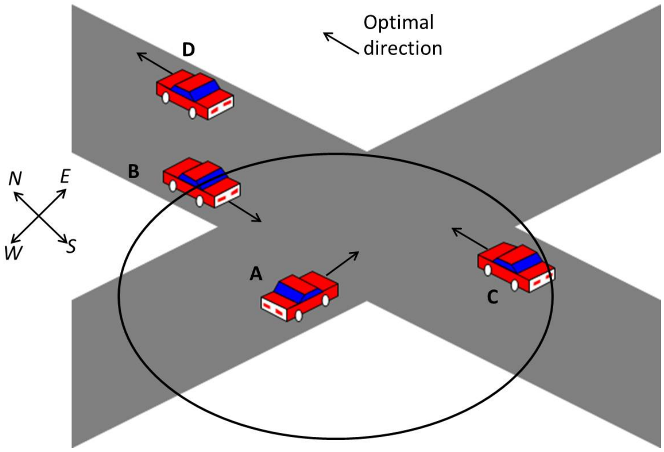


Figure 2.7: Selection of the next node to forward the packet.

and this is done by taking the connectivity of streets into account. On the other hand, when the network is dense and consequently connected in most parts, the main challenge in the design of the routing protocol is to minimize the delay by selecting non-congested routes that have a sufficient level of connectivity over time. With these two objectives in mind, in [51] was developed a Connectivity-aware Minimum-delay Geographic Routing (CMGR) protocol.

In this protocol the authors assumed that vehicles are equipped with Global Positioning System (GPS) receivers and they periodically send beacons reporting their positions to their neighbours. So, every vehicle can calculate the vehicle density in its immediate area. Also, it is assumed that vehicles are equipped with digital maps with detailed locations of streets and junctions.

In CMGR, any vehicle that wants to set up a route to any Gateway (GW) or Access Point (AP), generates a Route Discovery (RD) message including its Identity (ID), location, velocity vector, and the generation time of the message, and then broadcasts it in the network. Any intermediate vehicle that receives the RD attaches its location to the RD before rebroadcasting it. The intended recipient of the RD is any of the GWs in the network. When any intermediate vehicle receives the RD, it subtracts the generation time of the RD from the current time and drops the packet if the result exceeds the message lifetime.

In Fig. 2.8 we can see an scheme of an urban scenario, where a source car with geographical location (x_s, y_s) needs to reach the nearest access point $AP_d(x_d, y_d)$ to establish Internet connection. There are several junctions in the map, as we can see.

Among all the RDs that are received at a AP for the same request but coming from different routes, the AP selects the most appropriate one according to the route selection logic which will be described below. Then, based on the locations of the

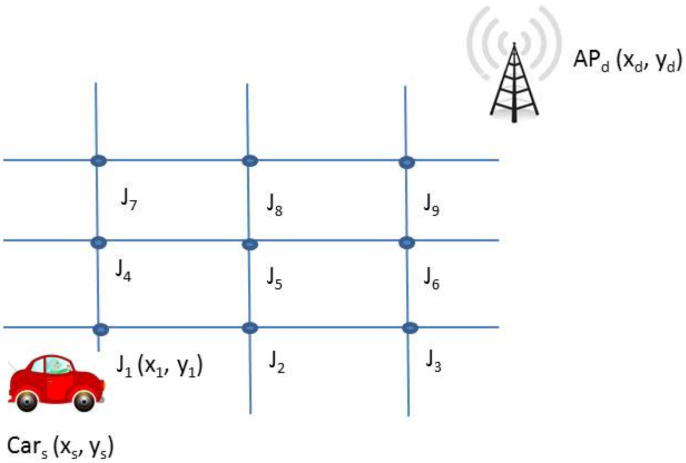


Figure 2.8: Urban environment scheme.

intermediate vehicles included in the selected RD, the AP determines all the junctions on the route the RD has come from as the junction sequence (JS). Then, the AP generates a route reply message comprising the JS, and the ID, location and velocity vector of the route-requesting vehicle already provided in the RD. The RR is sent back to the route-requesting vehicle along the JS by using a geographic greedy forwarding algorithm. In this algorithm any forwarding vehicle forwards the packet to the neighbour closest to the next intended junction in the JS or starts carrying the packet if a local maximum occurs. After receiving the RR, the route requesting vehicle will use the JS included in the RR for sending and receiving data packets to and from the AP.

One of the most important novelties of this protocol is the route selection process, where the connectivity of routes is taken into consideration to select the most appropriate route. They evaluate constantly the density of the streets, so they differentiate situations where vehicles are sufficiently dense from situations where vehicles are sparse. With this route selection logic, they make sure that in dense situations the route chosen has a minimum delay.

This proposal is adaptable to the density of vehicles in the network. In order to deal with network disconnections in sparse situations, the routes with higher vehicle densities are prioritized and when the network is dense, less congested routes with minimum delays among routes with enough connectivity level are favoured.

2.5.7 Movement Prediction-based Routing (MOPR)

MOPR [52], is a routing protocol for VANETs, which improves the routing process by selecting the most stable route in terms of lifetime with respect to the movement of vehicles. The authors estimates the stability of each communication link in the network in terms of communication lifetime and then selects the most stable route that is composed by the most stable intermediate links from the source till the destination.

MOPR is an algorithm that can be adapted to several existing routing protocols. It was adapted to AODV and then to GPSR to analyse the performance seeking to improve the results using position based routing protocols, such as GPSR.

In MOPR, each vehicle calculates the Link Stability (LS), which is the time that a neighbour will be in transmission range of another neighbour. A highest value of LS minimizes the probability of link failures during communications. To calculate this value the neighbour uses information like communication range, position and speed.

When a vehicle wants to send or forward data using MOPR over GPSR, it first estimates the future geographic location after a duration time t in seconds for each neighbour. Then, it selects a next hop (the closest neighbour to the destination) which has not a future location out of its communication range after the time t. MOPR, using metrics as position and speed decreases the data loss and increases the routing performance.

2.5.8 An improved GPSR Routing Protocol

In [53], they proposed an improvement of the GPSR protocol and redesigned it for VANETs. This improvement over GPSR focuses on improving the greedy forwarding strategy of GPSR by introducing factors such as vehicle moving direction, speed, and traffic density into the packet forwarding decisions.

The routing strategy is based on the fact that each node obtains its own coordinate information and speed at time t. Also, it knows these information from all neighbour nodes by receiving hello messages. With these data, it calculates the distance to each neighbour.

The selected next hop will be the neighbour with minimum value of distance. If there are more than one, will be chosen the node with lower speed, trying to ensure that the communication link will be maintained a longer time.

This proposal is based is the use of several metrics as direction, speed and density that are important in VANETs. Is not suitable to sparse scenarios.

2.5.9 GPSR with Movement Awareness (GPSR-MA)

GPSR-MA [54] exploits not only the position, but also takes advantage of certain information about the vehicle like direction and speed of movement of vehicles.

Routing decisions are based on speed, that is an absolute value measured in m/s; and the direction of movement of the vehicle which is calculated as an absolute angle between node's speed vector and the segment connecting it to the destination.

These values are available since every node instantaneously updates its location coordinates and speed of its neighbours.

Finally, the routing decision is based on three metrics: speed (speed should be close to the speed of current node), distance (node closer to destination) and movement

(movement direction approaches to destination) with the same weight each one.

2.5.10 Greedy Perimeter Stateless Routing with Lifetime (GPSR-L)

GPSR-L [55] as [52] calculates the link lifetime to estimate the quality of link and the duration of the neighbour's existence.

In [55] the lifetime is defined as the amount of time a node exists in the range of another and viceversa. Using two extra fields in hello messages (speed and direction) is possible calculate if neighbours are or not in communication range, and update its neighbour list. The goal of doing this is to avoid packet losses in highly mobile environments.

The main drawback is not uses any mechanism to prevent losses when no neighbours are in transmission range.

2.5.11 Hybrid Position-Based and DTN Forwarding

Taking into consideration that some application in VANETs can tolerate a certain delay, [56] proposes a hybrid forwarding technique to efficiently route data packets by combining position-based forwarding (such as GPSR [49]) and the idea of store-carry-forward from Delay Tolerant Networks [4]. In this proposed method, when the packet enters a perimeter mode, according to the driving direction of the vehicle and the delivery direction of packet, the vehicle will determine to either hold or deliver this data packet.

The basic idea is an smartly switching mode between position-based forwarding (geographic routing protocols like GPSR) and store-carry-forwarding. The selection should be made based on the current traffic situation and location of neighbouring vehicles.

When the packet is carried by a vehicle, the neighbour list is periodically checked trying to found a possible next hop towards destination. A maximum timer is established in order to discard packets stored.

This improvement increases the chances of final delivery, mainly in sparse networks where the links are intermittently. At the cost to increases end-to-end delay.

2.5.12 Improvement of Epidemic Routing for VANETs

In [57] was proposed a data forwarding mechanism that combines Epidemic routing, position information and moving direction of a node. The epidemic mechanism adopts the concept of store-carry-forwarding where each node stores data packets in the buffer, and whenever the node meets another node, it forwards a duplicate data packets. This idea consume significant networks resources.

To reduce the wasted of networks resources the authors in [57] determines if it should forward the packets to another node based on its geographic position information and moving direction. The two condition to fulfill in order to receive a duplicate of the forwarding data are: the neighbour node is closer to destination than the source node and the neighbour moves toward the direction of destination.

2.5.13 Multi-Metric Opportunistic Routing (MMOR)

MMOR [58] is a routing protocol based on opportunistic forwarding which imports the multi metrics into analysis of the best opportunistic next forward node while route link is being established. Opportunistic routing protocol is applied, the node does not have a predefined strategy to choose the next node for forwarding packet to destination. The node in opportunistic routing mode will make decision that is justified by the current circumstances. The neighbour nodes' collect information such as, its own position, the street topology and calculate the neighbours' density. Each vehicle also records its current packet process load, moving direction and velocity. MMOR consider take into account several metrics to choose the forwarding candidate. The metrics selected are the distance between the candidate node and the destination node, the packet process load of the candidate node, the moving direction and velocity of the candidate node and the neighbour node density of the candidate node. The evaluation of this protocol was made in a sparse scenario considering the area of evaluation.

2.5.14 Summary of routing protocols for VANETs

After a wide research about routing protocols to VANETs we can notice which are the more important characteristics that a new routing protocol designed for VANETs should have.

We identify the main metrics to be considerer into a vehicular routing protocol. The distance as one of the most important metrics to consider because vehicle prefers to choose the neighbour closest to destination, this increases the chances to delivery faster the packets to destination. The density also plays an important role in vehicular scenarios due to the ad hoc nature of the vehicular networks. Depending on the density of the scenario all the behaviour could be different. A sparse scenario should consider an optional mechanism to reduce losses, due to the low options to select a optimal next forwarding node. In contrast a dense scenario should consider forwarding decisions that reduce delay. Also the speed is a metric that affect the variant topology in VANETs, due to the relation of the speed in the variation of the topology, the time of the communication links and the trajectory of each vehicle.

Thanks to all the theoretical analysis, it is possible to conclude that speed, density and distance are the metrics that should be included in the development of our own proposals that should improve the already routing protocols already existed in the literature.

In the next chapters we present our proposals and improvements over some of the principal routing protocols for VANETs recently described in the literature.

2.6 Conclusions

Safe navigation support through wireless V2V or V2I communication has become an important priority for vehicle manufacturers and communications standards organizations. New standards are emerging for V2V communications (i.e. IEEE 802.11p). Although safe navigation and safety in general has always been the main motivation behind V2V and V2I communications, vehicular networks has the potential to drastically improve the driver's quality of life.

The specific characteristics of VANETs make the design of routing protocols a challenging task. Vehicular ad hoc routing must use as much information about the environment (neighbours, road topology, obstacles) as possible. This helps the protocol when deciding the most appropriate next hop for a packet.

In this thesis we have analysed and studied the main characteristics of Vehicular Networks over which were going to develop our framework. In next chapters we present some contributions to improve the routing in VANETs and provide a certain level of anonymity and QoS. To achieve this objective we have developed a new routing protocols taking as a base the GPSR protocol to offer improvements in vehicular scenarios.

Chapter 3

Contribution to improve GPSR in Vehicular Ad hoc Networks

3.1 Introduction

As we have seen in Section 2.5.3, Greedy Perimeter Stateless Routing GPSR [49] is a routing protocol for wireless networks that uses the position of neighbours to take packet forwarding decisions. GPSR makes greedy forwarding decisions taking into account the immediate neighbours who belong to the corresponding transmission range. Actually, GPSR finds immediately new routes using local topology information and due to that, GPSR becomes a good solution in vehicular networks where mobility is high. The algorithm consists of 2 phases, *greedy forwarding* and *perimeter forwarding*. This protocol assumes that each node knows its own location as well as the positions of all neighbours. Knowing the position of all neighbours in its own transmission range, the next hop to be chosen will be the nearest neighbour to destination.

In this chapter a set of improvements to GPSR are proposed, implemented and evaluated in order to obtain a better performance than GPSR. Basically, our proposal includes two important features: we add the use of a local buffer to minimize losses and we also use the capability of being building-aware for a best next forwarding node selection in a city environment.

The results of this chapter was submitted to the IEEE Latin America Transactions in the paper “Design and evaluation of GBSR-B, an improvement of GPSR for VANETs”, *submitted* [59].

Table 3.1: New format of the hello messages.

ID	***Position (x)***	***Position (y)***	***Speed***
32 bits	16 bits	16 bits	16 bits

3.2 Greedy Perimeter Stateless Routing using Buffer

The first proposal to improve GPSR needs a precise knowledge of the neighbours and destination positions and instead of using the *perimeter mode*, we propose to use a **buffer solution**. GPSR with buffer is called **GPSR-B** and it includes the location information of the neighbours to choose the optimal next forwarding node. The general idea is to store packets in a local buffer of the node and try to send them later if the node detects a neighbour as a possible forwarding node. A possible forwarding node is any node that satisfies two conditions:

- It is in the transmission range of the current forwarding node.
- It is the nearest neighbour to the destination node among all the neighbour nodes.

3.2.1 Neighbours actually reachable

GPSR-B tackles the important issue of seeing which neighbours are actually reachable. This feature is of paramount importance to determinate if a neighbour in the neighbour list could be a good forwarding node. The accurate information about the current position of a neighbour has a strong impact in the performance of GPSR-B, because knowing this information makes the node aware of which neighbours are reliable to be next forwarding nodes. At the same time, it avoids sending packets to an unreachable node.

GPSR-B uses signalling hello messages between neighbours similar to other proposals such as [53] [54] [60] [61]. We use three new fields included in the hello messages of GPSR-B which are shown in Table 3.1:

- *ID node*: This field has 4 bytes and identifies the node.
- *Position*: The position field uses 4 bytes to transmit the geographical coordinates of the node; 2 bytes for position in the x-axis and 2 bytes for position in the y-axis.
- *Speed*: It uses 2 bytes, and stores the current speed of the node. This helps to compute the future position of the node.

The hello messages can be sent as frequently as needed (higher frequency will obtain higher precision), but at the same time we should be aware that sending them very often may produce undesired congestion and collisions. However, tests have been done about this parameter showing that 1 hello message per second is a suitable frequency, same as the hello message interval in the AODV protocol. A shorter or longer interval could be used when a high (highways) or slow (traffic jams) node mobility is detected.

GPSR-B sets the nodes that are reachable in the same way than MOPR [52] over GPSR but within a slight difference, which is: instead of computing future positions for each neighbour and verifying if the distance between the node and its neighbour is higher than the transmission range, GPSR-B estimates the current neighbour's position but at the same time restricts the maximum distance between the node and its neighbours depending on the speed of the nodes, i.e. the maximum distance within which the neighbour could be found during a second of time. For example, considering a maximum speed of a node of 14 m/s and a transmission range of 250 m, the restriction in this case is $250 - 14 = 236$ meter. We take this it into account to ensure that in the next one second this vehicle will still be inside the transmission range.

3.2.2 Greedy Forwarding decision

To take a forwarding decision, GPSR-B uses the same criterium as the original GPSR and also as MOPR (used over GPSR). It consists on choosing the nearest neighbour to destination knowing that GPSR does not include any modification in the format of data packets and only includes the position of the destination with a 5 bytes field to select the next hop. Further fields or techniques could be implemented to maintain the location of the destination node updated (in the scenarios evaluated in this thesis, the position of destination is fixed). The pseucode to choose the next hop is presented in Algorithm 1.

Algorithm 1 . Forwarding scheme in GPSR-B.

```
Require: nodeSelected = firstNodeList
Require: temp = 0
Require: distanceMin = Distance(nodeSelected, destination)
1: while temp != totalNeighbours do
2:    currentDistanceNode = Distance(currentNode, destination)
3:    if currentDistanceNode < distanceMin then
4:       nodeSelected = currentNode
5:    end if
6: end while
7: if Distance(nodeSelected, destination) < Distance(source, destination) then
8:    NextForwardingNode(nodeSelected)
9: end if
```

The algorithm looks for the first node in the neighbour list (firstNodeList) and then assigns it as *node selected*. After that, the node selected is compared to the rest of the nodes in the list within coverage range and if one of these nodes is closer to the destination than the current candidate, then there is a new *selected node* (lines 1-4). The *selected node* will be the *next forwarding node* (lines 7-8).

In case that there is no neighbour closer to destination than the sender node (or the current forwarding node) packets are stored in a buffer (in order to be sent latter). This option will be explained in Section 3.2.3.

3.2.3 Use of a local buffer as an alternative to the perimeter mode

An important drawback of GPSR is the implementation of *perimeter forwarding*, because it is not clear when the algorithm switches its mode to greedy forwarding again. In addition, mobility can induce routing loops in the *perimeter mode* [62].

To avoid the problems found by using perimeter forwarding, GPSR-B stores the packets in a buffer when there is no neighbour that satisfies all the requirements needed to be a *next forwarding node*. If at least one of the two conditions (i.e. being actually a neighbour and being closet to destination than the current carrier node) required to be the next hop is not satisfied, then packets are stored in the buffer. If the buffer is full, packets are dropped.

GPSR-B tries to forward the packets stored in the buffer periodically, while it looks for a neighbour that meets the requirements to be a proper forwarding node. This period of time was established in 1 sec, because was frequent enough to detect a topology change. For each destination the packets are stored in arriving order and sent in the same order, so the implemented buffer is a FIFO queue.

GPSR-B stores packets in the buffer and periodically looks for a neighbour that can satisfy the requirements to be the next forwarding node. Every period of time the buffer looks for a new node candidate. If a candidate fulfills the requirements, the stored packets are forwarded to that node.

In the algorithm 2, we show the buffer algorithm in GPSR-B. We observe the two reasons to store packets in the buffer, if there is no neighbour in transmission range (line 1) or if no neighbour in transmission range is closer to destination than the current node (line 10). If the buffer is full that packet will be dropped; otherwise is stored in the buffer (lines 3-7 and lines 11-15).

3.3 Greedy Buffer Stateless Routing Building-aware

An important issue that one should face when trying to design a routing protocol for VANETs in urban scenarios, is the presence of obstacles such as buildings, trees and other obstacles which are present in the cities. Greedy forwarding in GPSR is often restricted because direct communication between nodes may not exist due to theses obstacles. In this section, we will present a new modification of GPSR called Greedy Buffer Stateless Routing Building-aware (**GBSR-B**) which focuses on two important enhancements: a) It takes into account the presence of obstacles in the next forwarding decision node and b) it selects the best way to make the buffer management.

Algorithm 2 . Buffer Logic in GPSR-B.

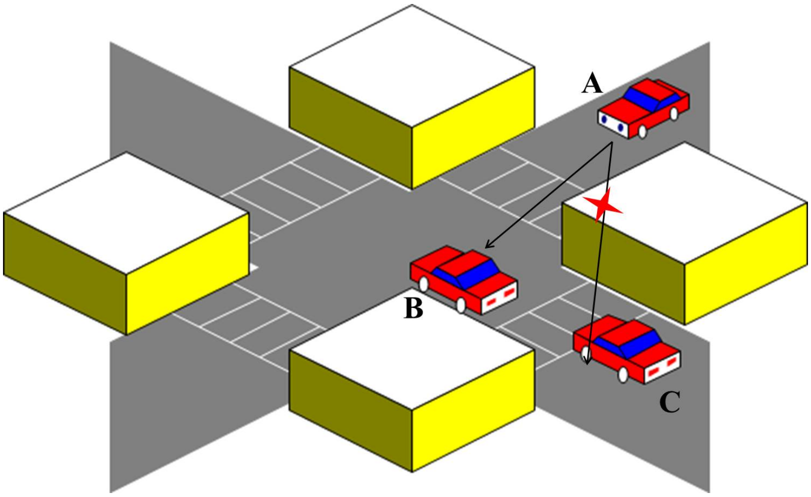
```
print To buffer when no neighbour in transmission range
if NeighbourList == 0 then
   if bufferFull then
      dropPacket
   else
      packetToBuffer
   end if
end if
print To buffer if no neighbour in transmission range is closer to destination than
   current node
if Distance(currentNode, destination)> Distance(source, destination) then
   if bufferFull then
      dropPacket
   else
      packetToBuffer
   end if
end if
```

3.3.1 Presence of buildings in Manhattan scenarios

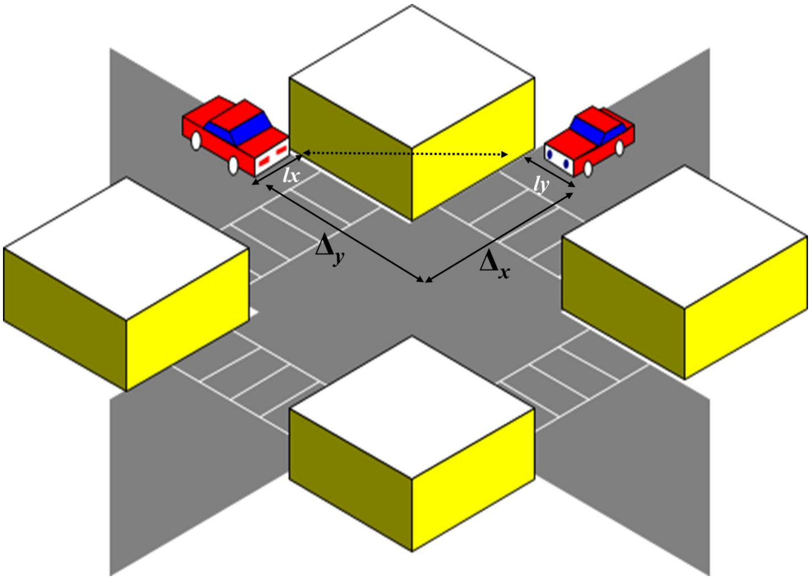
In [22], a propagation model called Building Model (BM) was presented. This model takes into consideration that at a frequency of 5.9 GHz (i.e. the frequency band of the IEEE 802.11p standard), the signal is highly directional and will experience a very low depth of penetration. Hence, in most cases, buildings will absorb radio waves at this frequency making communication only possible when vehicles are in Line Of Sight (LOS). Fig. 3.1(a) shows an example of this model where yellow rectangles represent buildings. In the Two-Ray Ground model, vehicle C may receive the message from A. Nevertheless, with the Building Model, only communication between vehicles A and B is possible. Vehicle C does not receive the message from A due to the presence of a building.

In a Manhattan-style visibility scheme, where vehicle movements can only be vertical or horizontal, two vehicles in different streets are in LOS considering Fig. 3.1(b), where:

- (x_1, x_2) and (y_1, y_2) are the coordinates of the vehicles.
- l_x is the street width in the x coordinate.
- l_y is the street width in the y coordinate.
- Δ_x is the absolute difference between x coordinates of the two vehicles $\Delta_x = |x_1 - x_2|$.
- Δ_y is the absolute difference between y coordinates of the two vehicles $\Delta_y = |y_1 - y_2|$.

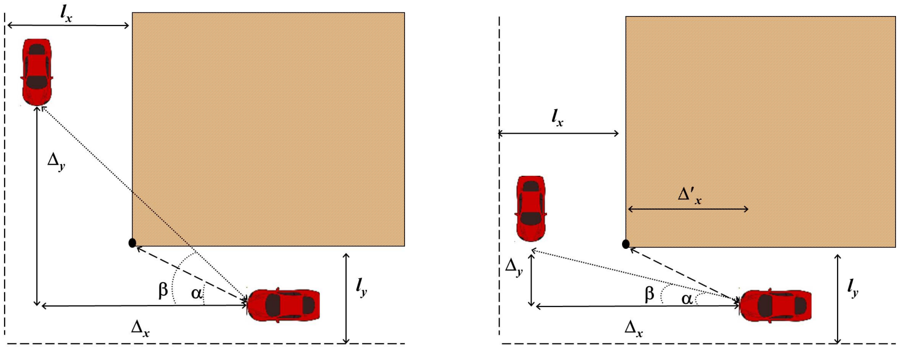


(a) Building model example.



(b) Manhattan-style visibility scheme.

Figure 3.1: Visibility schemes.



(a) Vehicles are out of LOS. (b) Vehicles are in LOS.

Figure 3.2: Vehicles in LOS in a Manhattan scenario.

In Fig. 3.2(a) we observe that vehicles are out of LOS (Line Of Sight) when $\beta \geq \alpha$, and vehicles are in LOS when $\beta < \alpha$. Equation (3.1) explains the condition to be in LOS.

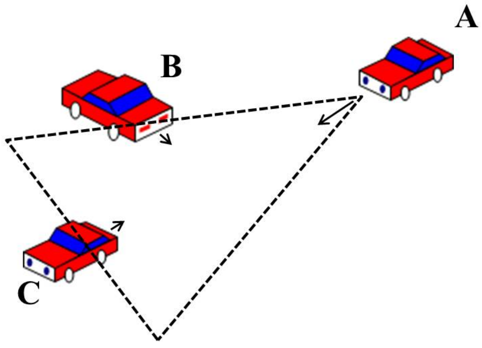
$$\begin{aligned} \beta = \arctan \frac{\Delta_y}{\Delta_x} < \alpha = \arctan \frac{l_y}{\Delta'_x} \\ \Delta'_x = \Delta_x - \frac{l_x}{2} \\ \frac{\Delta_y}{\Delta_x} < \frac{\frac{l_y}{2}}{\Delta_x - \frac{l_x}{2}} \\ -\frac{l_x}{2} \cdot \frac{\Delta_y}{\Delta_x} + \Delta_y < \frac{l_y}{2} \\ -l_x \cdot \frac{\Delta_y}{\Delta_x} + 2\Delta_y < l_y \end{aligned} \tag{3.1}$$

Therefore, there is LOS in a Manhattan scenario if and only if equation (3.2) is true.

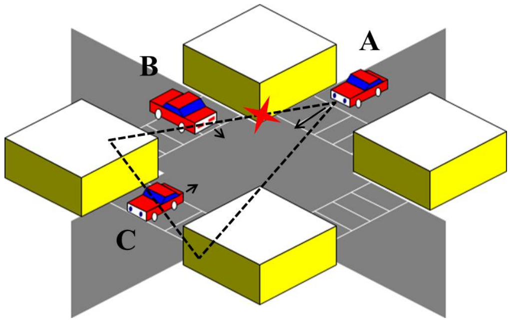
$$(\Delta_x < \frac{l_x}{2}) \bigvee (\Delta_y < \frac{l_y}{2}) \bigvee (-l_x \cdot \frac{\Delta_y}{\Delta_x} + 2\Delta_y < l_y) \tag{3.2}$$

3.3.2 Presence of obstacles in a city

In NCTUns [63] the design of a scenario is made in a graphic mode. The code of the generated scenario is stored in a scenario file. During simulation, a function called *Check_obstacles* is called and returned if there is a visual obstacle for the driver in the area between source and destination vehicles.



(a) Driver's viewpoint only considering the relationship of vehicular position.



(b) Driver's viewpoint considering additionally the locations of all view obstacles

Figure 3.3: Two phases to simulate a driver's viewpoint.

NCTUns uses vehicular positions to analyse the presence of obstacle objects. If the straight line between a vehicle's position and the next hop position crosses any obstacle's rectangular area, then from the vehicle driver's viewpoint, the retrieved destination vehicle should not be seen.

For example, in Fig. 3.3(a) vehicle A tries to retrieve the nearest vehicle that is located within a sector area in front of vehicle A. The function *Check_obstacles* searches if there are obstacles that block the transmission area of A. As we can see in Fig. 3.3(a), vehicle B and vehicle C are in transmission range of vehicle A. When vehicle A receives hello messages from vehicles B and C it checks if there is any obstacle situated between source vehicle (let us say vehicle A) and the possible next hop. As we can notice from Fig. 3.3(b), the obstacles around the crossroad block the viewpoint from vehicle A. The visual area from vehicle A does not include the whole sector area because the visual line between A and B is blocked. Therefore, vehicle B should not be seen by vehicle A and the nearest vehicle in front of vehicle A is vehicle C instead of B. This simple algorithm is implemented and used in the simulator to give realism to the mobility model and this could be used in any kind of scenario (Manhattan or real city maps)

3.3.3 Detection of obstacles in GBSR-B

Verifying the three conditions, i.e., actually being in coverage range, having less distance to destination and being in LOS, if the candidate fulfills all requirements, packets are forwarded to that candidate; otherwise they are buffered in a local buffer of the current carrier node.

Using the building-aware scheme in GPSR-B if neighbours are not in LOS, packets are stored in the buffer. In addition, an improvement of the buffer decision is added and explained in Section 3.3.4.

It is important to mention that although the building-aware scheme could be implemented without buffer, it would have no sense because without buffer it would be more difficult to find quickly a suitable next forwarding node that satisfies all the requirements. As a result of that, packets would be dropped and packet losses would increase dramatically, see Algorithm 3.

3.3.4 Improvement of the buffer management

We analyse three ways to initialize the new forwarding process of the packet stored in the local buffer of a node.

- **Proactive mode**: It uses a fixed period of time to try to forward packets that are stored in the buffer. Here, the buffer attempts to send the packet every t seconds (low value of t means that more frequently the process is repeated). Considering that VANET nodes are free of energy consumption problems and enjoy no problem in computation power, this time t can take small values depending on the scenario. t is set to be 1 second in our case.

- **Reactive mode**: The buffer tries to send the stored packets each time a hello message is received. The reception of a hello message is a signal that a change could have been produced in the neighbour list and therefore it is a good moment to find an optimal next forwarding hop.

- **Mixed mode**: It uses both methods. It tries to find the best next hop every t seconds but if a hello message is received before, it will try to find an optimal forwarder too in that moment.

The value of t in proactive mode could be set depending on the mobility of nodes, the stability of the neighbours or any other criteria. If a packet is not sent after a threshold time, it will be discarded. In addition, the implementation of the buffer could be considered as a carry and forwarding strategy which is very used in intersection-based routing protocols. The buffer allows the protocol to store those packets that

Algorithm 3 . Forwarding scheme in GBSR-B.

```
print  Searching the first neighbour node in transmission range
repeat
  nodeSelected = neighbourPosition(temp)
  distanceMin = Distance(nodeSelected, destination)
  temp ++
until  Distance(nodeSelected, destination) < transmissionRange ||||
  Check_obstacles(nodeSelected, destination)
print  Looking for closest neighbour to destination
while temp != totalNeighbours do
  currentNode = neighbourPosition(temp)
  if Distance(currentNode, destination) < transmissionRange &&
    Check_obstacles(currentNode, destination) then
    distanceCurrentNode = Distance(currentNode, destination)
    if distanceCurrentNode < distanceMin then
      nodeSelected = currentNode
    end if
  end if
end while
if Distance(nodeSelected, destination) < Distance(source, destination)&&
  Check_obstacles(nodeSelected, destination) then
  NextHop(nodeSelected)
else
  packetToBuffer
end if
```

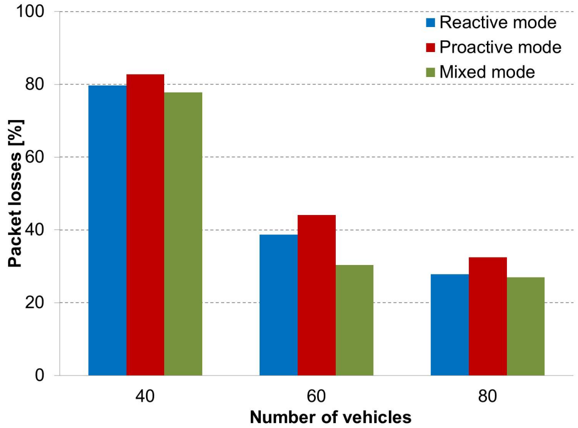


Figure 3.4: Percentage for losses depending on the method to forward packets from the buffer.

would be dropped and now they have a chance to be forwarded. Also, it avoids to switch constantly between the two modes operation in GPSR (greedy forwarding and perimeter forwarding mode) since GBSR-B works only in greedy forwarding mode.

After the analysis of the three modes of using the buffer, we decided to use the mixed mode which presents a slightly improvement in terms of percentage of losses in our scenarios. Results are shown in Fig. 3.4. We observe that using a mixed mode (green bar) we obtain a little improvement compared to the other two methods: reactive (blue bar) and proactive (red bar). The reactive mode (i.e. looking for new nodes after receiving hello messages) improves the performance compared to the proactive mode (i.e. trying to forward the packet every 1 sec.). The same results were obtained for the three densities evaluated (40, 60 and 80 nodes), as it can be seen in Fig. 3.4.

3.4 Comparison of GPSR and GBSR-B

This section describes the scenarios that we have used to carry out a performance evaluation of our proposal GBSR-B compared to AODV and GPSR. In Section 3.4.1, scenarios are presented and simulation settings are explained. In Section 3.4.2 results are shown with their analysis and comparison.

3.4.1 Simulation scenarios

In order to evaluate the behaviour of our new proposal, we have carried out several simulations to analyse the performance of our new implementations using the open source network simulator NCTUns 6.0 [63] where GPSR and our proposal GBSR-B

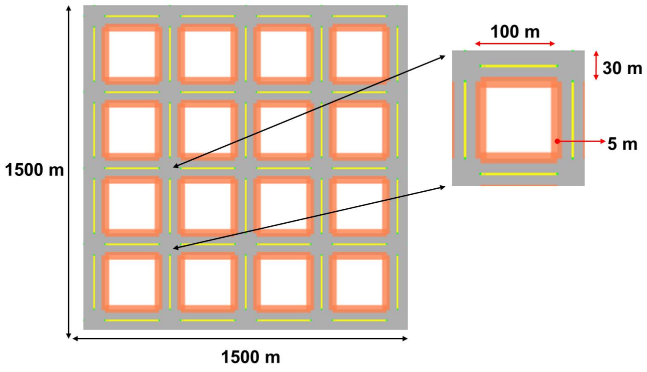


Figure 3.5: Length of the streets in the scenario.

have been implemented.

Four scenarios have been used to analyse the performance of GBSR-B and to compare it to GPSR and AODV. Each scenario has a maximum speed of the node and five different densities of nodes. The simulation city area is 1500m x 1500m, each street has a length of 100 m and intersections of 30 m. In Fig. 3.5, the length of the streets are depicted as well as the buildings (denoted by orange lines of 5 m width) that attenuate totally the transmission signal. The mobility model is Manhattan, which is generated by Citymob [41]. In each scenario 50% of the nodes are sending data (1000 bytes per packet) to one fixed destination during 1000 sec. The main simulation settings of each scenario are shown in Table 3.2.

Table 3.2: Simulation settings in urban scenarios.

Parameter	**Value**
Area	1500 m x 1500 m
Number of vehicles	40, 60, 80, 100, 120
Maximum vehicle speed	30, 50, 70, 90 km/h
Transmission range	250 m
Sensing range	300 m
Mobility model	Manhattan
Mobility generator	Citymob
MAC specification	IEEE 802.11b
Bandwidth	11 Mbps
Simulation time	1000 s
Maximum packet size	1000 bytes
Routing protocol	AODV, AODV without cache, GPSR, GBSR-B

3.4.2 Simulation results

To obtain reliable results we have averaged the values obtained from 5 different simulations and we have calculated the confidence interval of 99%. After that, we have analysed the obtained results and drawn the mean percentage of packet losses, average delay, average number of hops and throughput achieved for the received packets.

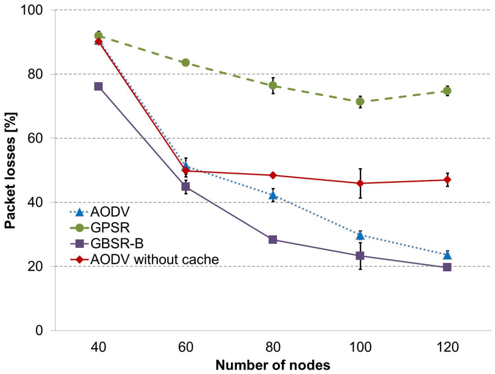
Our first case has 30 km/h as maximum speed of the nodes. Fig. 3.6(a) shows the percentage of losses for the three evaluated protocols where we can clearly notice that our proposal GBSR-B outperforms both GPSR and AODV protocols. GPSR obtained the higher losses because it does not make use of any buffer. As we know, GPSR searches for the nearest node to destination and if it does not find a node which is better than the carrier node itself, the packet will be dropped. AODV shows a bad performance for low density of nodes because AODV has to establish a full end-to-end path before sending packets, so with high densities losses decrease due to the easier way to establish end-to-end paths.

In addition, having only one destination node in the scenario each AODV node stores in cache a path to achieve the destination, so in case that the path is broken, it would be more easier for the AODV node to find a new route (saving the RREQ/RREP process).

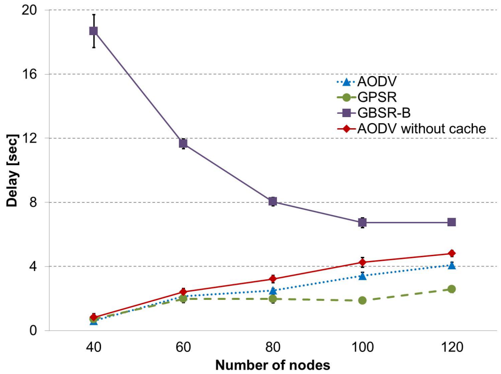
To analyse the importance of such cache feature, we have also implemented AODV without cache for a fair comparison with GPSR and GBSR-B which do not include any cache. The results show that AODV without cache and with a low number of nodes works similar to AODV with cache, but when the number of nodes increases losses increase because each time the path is broken it is necessary to establish a new path using RREQ and RREP messages. This means that when AODV uses a cache, it stores other possible paths to destination, so to find a new path could be immediate. But without the cache, each time the path is broken a new process to find an end-to-end path is initiated. During the time to find the new end-to-end path a high number of packet are dropped. Our new proposal GBSR-B shows the best results in all cases, even if with 120 nodes the difference is not very high compared to AODV. This is consequence of having a lot of neighbours (high density) in the transmission range that leads to more collisions that increases losses in GBSR-B protocol.

In Fig. 3.6(b) the average end-to-end delay is shown. It can be clearly seen that our proposal GBSR-B presents higher values than the other protocols due to the usage of a buffer which stores packets and retransmits them. This higher delay is the cost to achieve lower losses. In the case of GPSR, delays present maximum values of 4 seconds, while with GBSR-B delays are around 18 seconds in the case of a sparse scenario with 40 nodes. This is due to the use of the buffer, which decreases losses but with the cost of increasing the delay. This issue was solved in our next proposal presented in Chapter 5. We can conclude that in case of a sparse network the use of GBSR-B is recommended only for delay tolerant services.

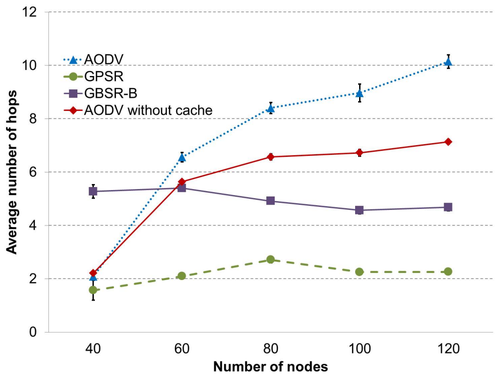
The average number of hops is shown in Fig. 3.6(c) where the results show that geographic protocols (GPSR and GBSR-B) present almost the same values



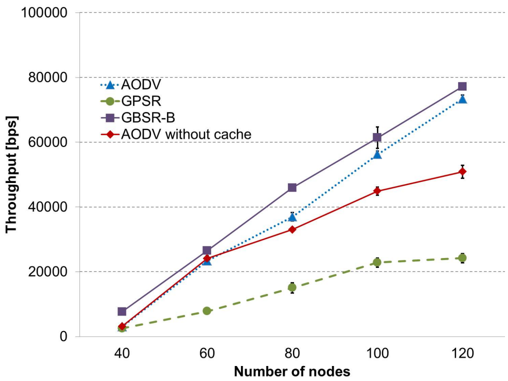
(a) Percentage of losses.



(b) Average packet delay.



(c) Average number of hops.

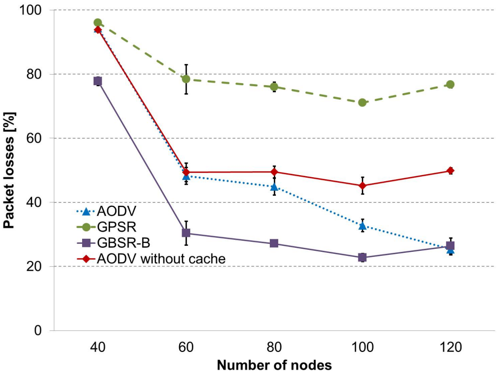


(d) Average throughput of received packets.

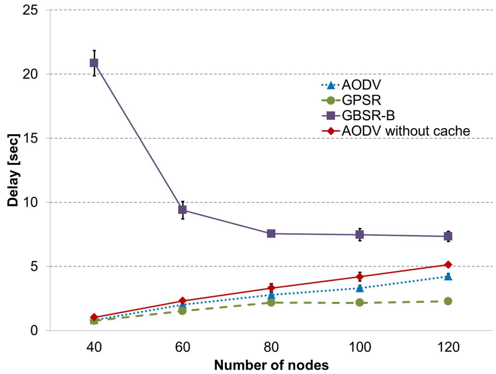
Figure 3.6: Urban scenario with buildings. Maximum speed 30 km/h. Performance of AODV, GPSR and GBSR-B protocols as a function of the density of nodes. (CI 99%).

independently of the network density because they are based on a hop-by-hop forwarding. Using GPSR the number of hops is around 2 hops while using GBSR-B it is around 5 hops. In case of AODV (with and without cache) we know that it has to establish a full path before sending the packet, so clearly the number of hops depends on the density of the network, i.e. higher densities lead to a high number of hops. It is shown that with a low density, the number of hops is 2 hops while with a high density it can reach 10 hops.

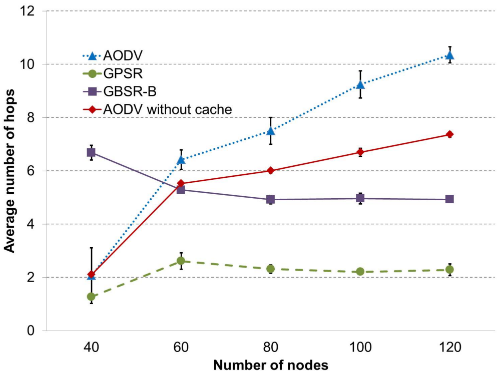
From Fig. 3.6(d) that represents throughput, we can deduce that GBSR-B values are the best in all cases. These results are related with the number of packets received in each case. When the percentage of losses is high (AODV in Fig. 3.6(a)) the throughput is low (AODV in Fig. 3.6(d)). The throughput is calculated taking into a count the



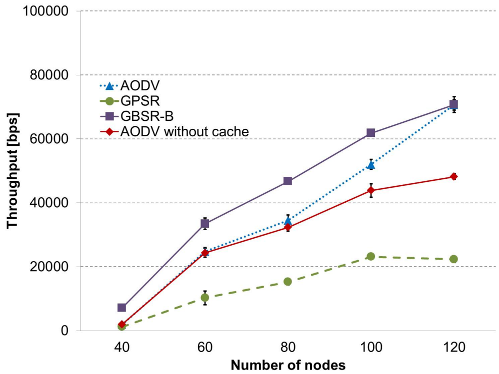
(a) Percentage of losses.



(b) Average packet delay.



(c) Average number of hops.

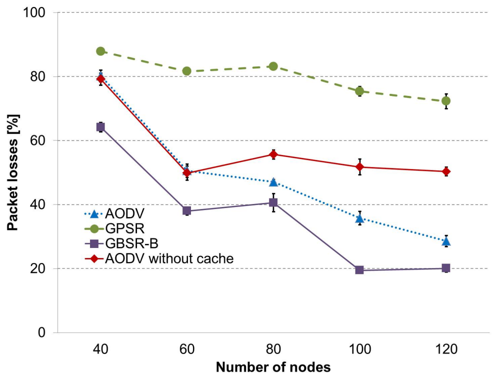


(d) Average throughput of received packets.

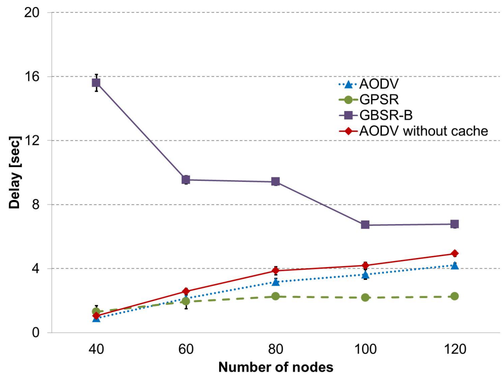
Figure 3.7: Urban scenario with buildings. Maximum speed 50 km/h. Performance of AODV, GPSR and GBSR-B protocols as a function of the density of nodes. (CI 99%).

packets arrived to destination, which in the case of AODV is a low number. Otherwise, GBSR-B delivers a high number of packets to destination (low percentage of losses, see Fig. 3.6(a)) and achieves a high throughput, see Fig. 3.6(c).

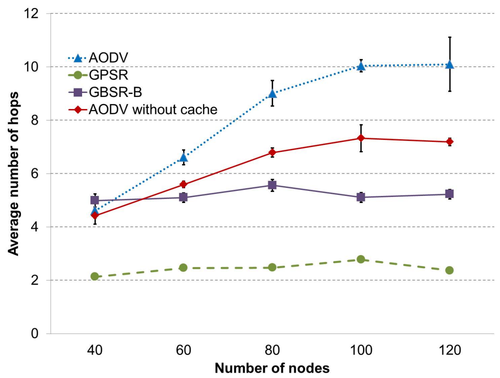
Our second evaluation is done with a maximum speed of the nodes of 50 km/h. Results of AODV (with and without cache), GPSR and GBSR-B are given in Fig. 3.7. Fig. 3.7(a) shows the percentage of losses, where GBSR-B has the best behaviour almost in all cases except for 120 nodes (extremely dense). GPSR presents the worst results with higher losses in all cases because packets are dropped when it does not find any nearest forwarding node to destination. AODV has a good performance with high densities, but still below than GBSR-B. AODV without cache has a bad performance when density of the nodes increases due to the increment of collision.



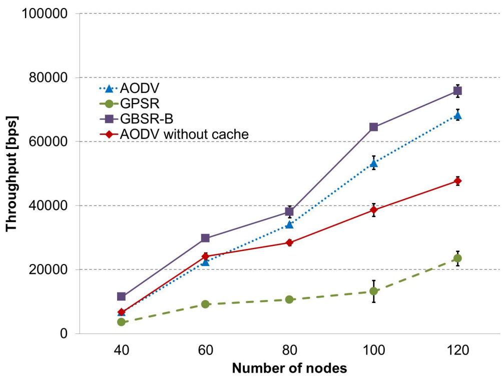
(a) Percentage of losses.



(b) Average packet delay.



(c) Average number of hops.

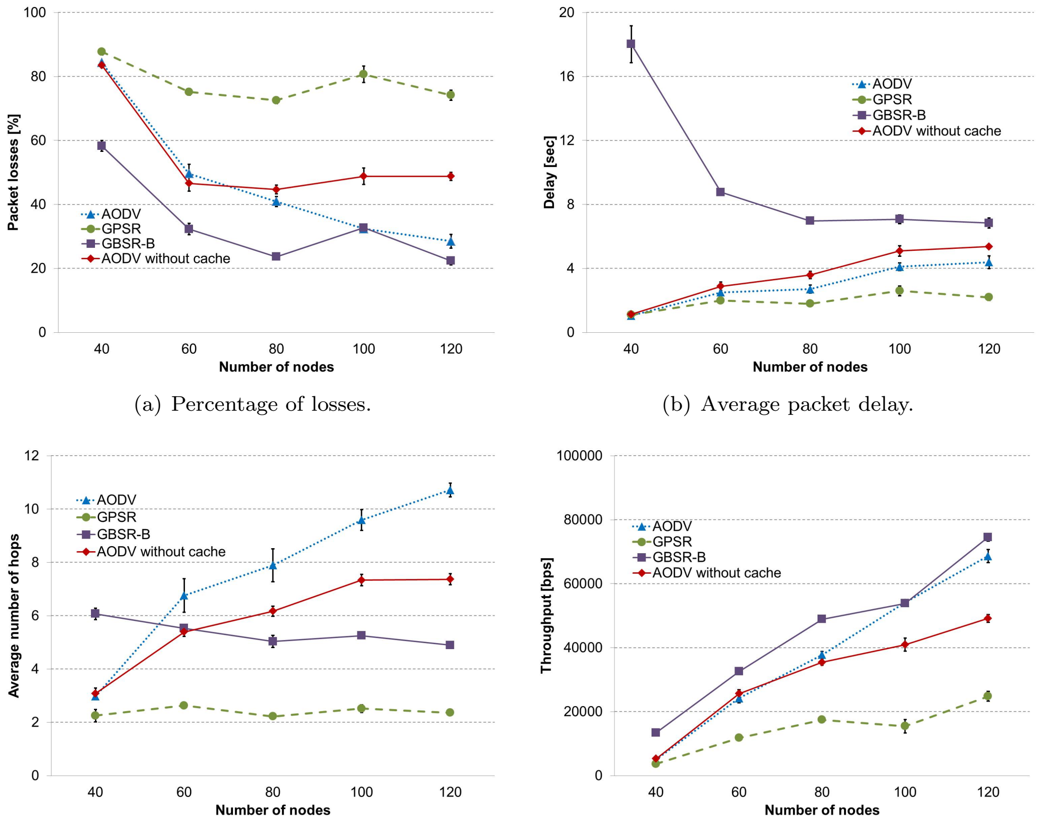


(d) Average throughput of received packets.

Figure 3.8: Urban scenario with buildings. Maximum speed 70 km/h. Performance of AODV, GPSR and GBSR-B protocols as a function of the density of nodes. (CI 99%).

Average end-to-end delays are shown in Fig. 3.7(b) and we can observe that delays increase using our proposal GBSR-B in cases of 40 and 60 nodes having 12 and 21 seconds respectively and this is because packets should stay more time in buffer when the network is sparse. The other three protocols evaluated present end-to-end delay values around 3 and 5 seconds. Fig. 3.7(c) shows the average number of hops and results are as expected, where geographic protocols such as GPSR and GBSR-B have the same values independently of the density of the network, because the selection is hop-by-hop while AODV (with and without cache) shows an increasing number of hops while the density of the nodes is increasing reaching paths up to 11 hops. Fig. 3.7(d) represents throughput, where GBSR-B obtained the highest values in all cases.

The third evaluation is done with a maximum speed of the nodes of 70 km/h and



(a) Percentage of losses.

(b) Average packet delay.

(c) Average number of hops.

(d) Average throughput of received packets.

Figure 3.9: Urban scenario with buildings. Maximum speed 90 km/h. Performance of AODV, GPSR and GBSR-B protocols as a function of the density of nodes. (CI 99%).

results are shown in Fig. 3.8. Following the same procedure we have done till now, Fig. 3.8(a) presents the percentage of losses, where we can notice that GBSR-B is the best although with a little difference than the other cases with 30 and 50 km/h, where in the case of having 80 nodes the percentage of losses was slightly higher than expected. In the same way, AODV without cache also presents notably change with 60 nodes, showing a decreasing value of the percentage of losses.

The rest of results presents almost the same tendency as in previous ones. End-to-end delays are shown in Fig. 3.8(b) and observing it leads us to notice that using GBSR-B in a sparse network has an end-to-end delay of 15 seconds because packets spend lot of time in buffer before being sent, while using other protocols the maximum value of this parameter is 5 seconds. The average number of hops is shown in Fig. 3.8(c) where we can see that the minimum number of hops using AODV (with and without buffer) is 5 hops while in previous cases it was 2 hops. Throughput is depicted in Fig. 3.8(d) and it follows the same tendency as the previous cases, i.e., Figs. 3.6(d) and 3.7(d).

Fig. 3.9 shows the last evaluation with a maximum speed of nodes of 90 km/h. At this speed, mobility of nodes is extremely high which produces frequent topology changes. All results under this case are slightly similar to the previous one (70 km/h), except the high losses seen using GBSR-B with 100 nodes. The reason is a slight increase in the number of hops in that denser scenario, since the higher number of nodes produces more hops to destination. AODV without cache with 60 nodes presents a decreasing value in the percentage of losses. These results are seen in Figs. 3.9(a), 3.9(b), 3.9(c) and 3.9(d).

In order to see the impact of the speed in the obtained results, we will analyse the results of packet losses, end-to-end delay, average number of hops and throughput as a function of the average speed of the nodes.

In the case of the percentage of packet losses, Fig. 3.10, one can notice that with a low number of nodes (Fig. 3.10(a)) when speed increases the average packet losses decreases, since at high speeds it is more probably to find a next hop in the case of GBSR-B and GPSR. In the case of AODV with high speed can achieve destination with a low number of hops. With 80 nodes (Fig. 3.10(b)) the results is more or lest constant except with 70 km/h where there is a little increase. But with 120 nodes (Fig. 3.10(c)) the results are very constant since there are enough nodes, so the results are only related with the density in the scenario.

In Fig. 3.11 we can notice the effect of the speed in terms of end-to-end delay. In the scenario with 40 nodes (Fig. 3.11(a)) the end-to-end delay is very low using AODV, GPSR and AODV without cache. These results are very related with the percentage of losses, because in scenarios with 40 nodes the average of packet losses was high producing a low end-to-end delay due to the calculation is based on the number of received packets. However, we can see that GBSR-B obtained high results due to the use of buffer. In the case of Figs. 3.11(b) and 3.11(c), scenarios with 80 and 120 nodes, respectively, notice that delays are generally low, because the density of the nodes increases and the number of hops increases. Consequently, the chances to arrive to destination increase.

The results of the average number of hops are presented in Fig. 3.12 where we can notice that they are very related with the density of nodes in the scenario. The scenario with 40 nodes presents a low number of hops, except GBSR-B that thanks to the buffer can maintain longer paths. In the case of the scenario with 120 nodes we see that the results are quite constant independently of the average node speed. This is due to the fact that the scenario is dense enough to not be affected by the speed of the nodes.

Finally, in Fig. 3.13 we observe the throughput in the case of scenarios with 40, 80 and 120 nodes respectively. We notice the same tendency than before. The results in our simulations are more related with the density of the scenarios. With a high number of nodes it is possible to get destination more often and to reduce packet losses.

Consequently, the throughput increases.

However, in all cases we confirm that our proposal GBSR-B improves the results compared to the other protocols.

3.5 Conclusions

In this chapter we have presented GBSR-B (Greedy Buffer Stateless Routing Building-aware), a novel protocol based on GPSR. GBSR-B is a geographic protocol with improvements as being aware of the buildings around and the optimal use of a buffer in case no forwarding node is found.

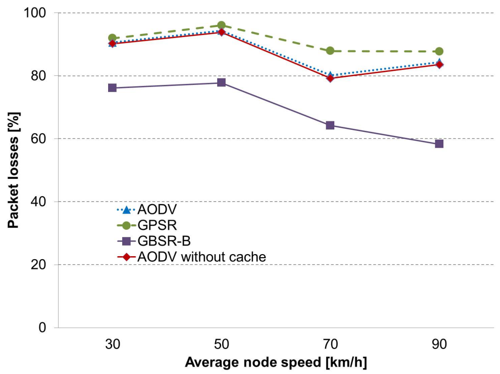
We have analysed two ways to detect the presence of buildings or general obstacles in urban scenarios by including the function building-aware where nodes can know if some obstacles (buildings, cars, etc) are presented. If that is the case, the transmission signal to destination or other neighbours could be blocked. Also, we include a carry-and-forwarding algorithm and we have improved the way to forward packets. We have tested three different ways to find a next forwarding node for those packets stored in the local buffer. We selected the best option to be implemented in the design of GBSR-B.

Finally, we have implemented GBSR-B in NCTUns 6.0 and tested its performance in urban VANET scenarios. After that, we have done a wide analysis of our proposal varying the speed of the nodes (30, 50, 70, 90 km/h) and density of nodes (40, 60, 80, 100, 120 nodes) showing that our proposal outperforms AODV and GPSR in almost all the cases.

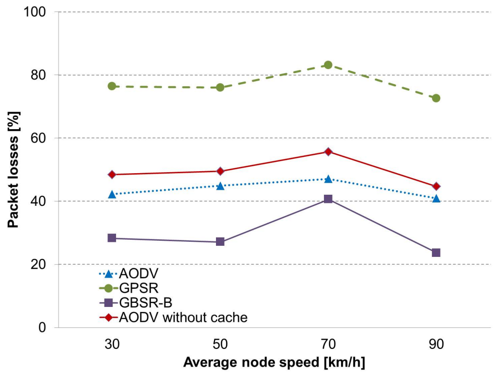
Reasons that make GBSR-B better is that it takes into account the main characteristics of VANETs. For example, it does not send messages to neighbours that will immediately go out of the transmission range, is capable to adapt quickly to topology changes and forwarding packets is used applying a hop-by-hop scheme, because to maintain a full path with a topology that varies frequently is almost impossible. Instead of dropping the packet when no proper neighbour is found, it stores packets till it finds a new forwarding node.

Results of our evaluations show the expectations from our GBSR-B where we could improve losses in all urban scenario with the price of increasing delays because some packets will be stored in the local buffer.

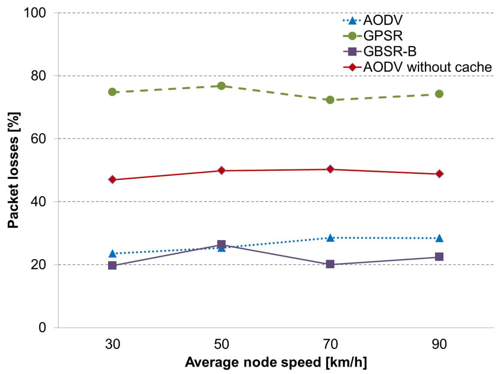
Our proposal is an excellent option in urban networks with delay tolerant applications. Although increasing the end-to-end average delay, GBSR-B offers a considerable low percentage of losses.



(a) Scenario with 40 nodes.

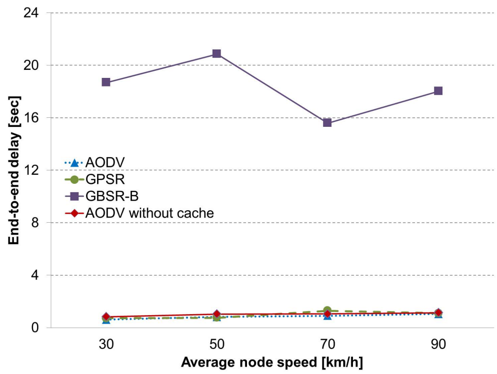


(b) Scenario with 80 nodes.

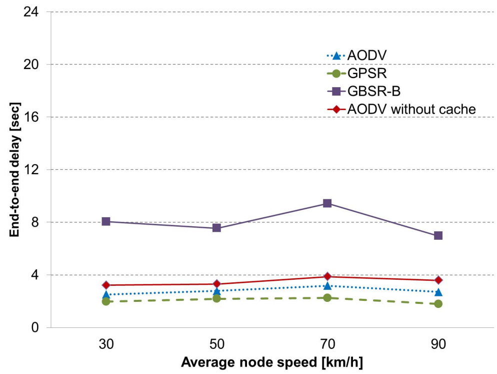


(c) Scenario with 120 nodes.

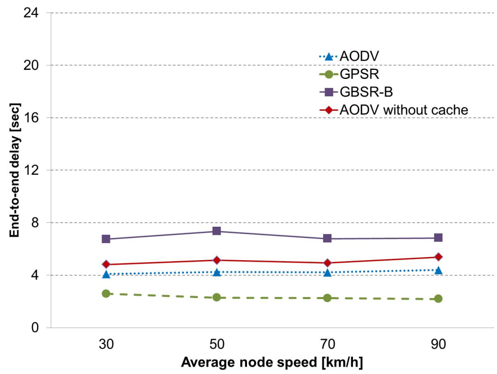
Figure 3.10: Percentage of packet losses. Performance of AODV, GPSR and GBSR-B protocols as a function of the average node speed.



(a) Scenario with 40 nodes.

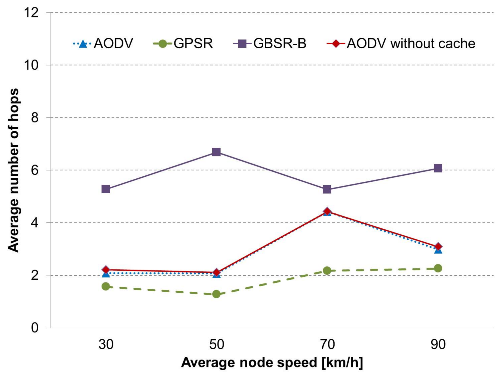


(b) Scenario with 80 nodes.

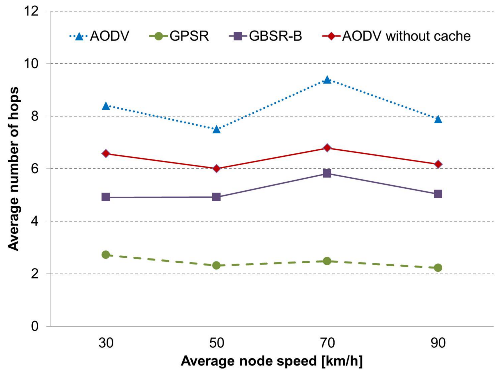


(c) Scenario with 120 nodes.

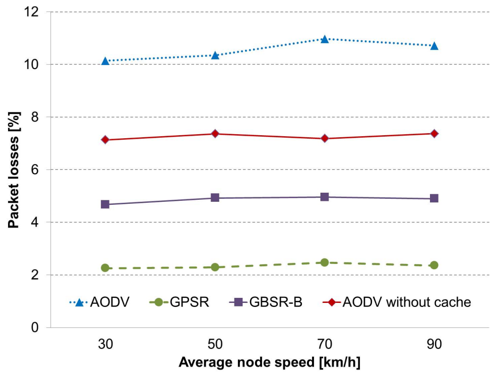
Figure 3.11: End-to-end delay of packets. Performance of AODV, GPSR and GBSR-B protocols as a function of the average node speed.



(a) Scenario with 40 nodes.

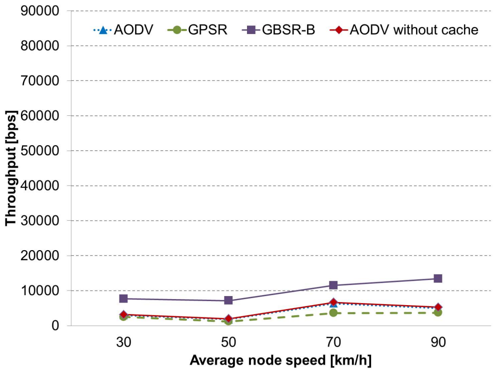


(b) Scenario with 80 nodes.

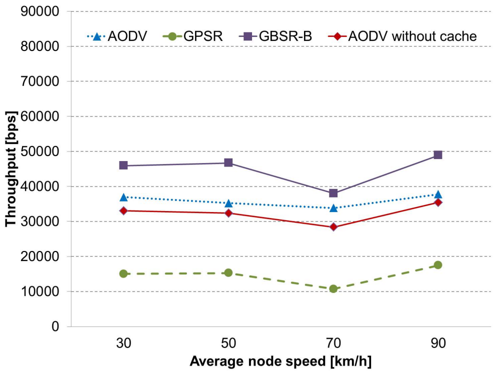


(c) Scenario with 120 nodes.

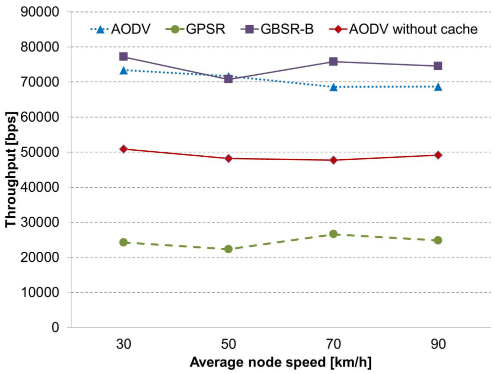
Figure 3.12: Average number of hops. Performance of AODV, GPSR and GBSR-B protocols as a function of the average node speed.



(a) Scenario with 40 nodes.



(b) Scenario with 80 nodes.



(c) Scenario with 120 nodes.

Figure 3.13: Average throughput. Performance of AODV, GPSR and GBSR-B protocols as a function of the average node speed.

Chapter 4

Available Bandwidth Estimation (ABE) for VANETs

4.1 Introduction

VANETs will enable applications in three primary directions: safety, traffic efficiency and infotainment. The first two categories are the main goals of vehicular technology. The third category influences on newly coined and existing services that naturally combine VANET and Intelligent Transportation Systems (ITS) [6] contexts, which can act as a market force. Infotainment implies the use of multimedia services (e.g. video streaming) that require a certain amount of network resources to run correctly.

In this section, we present a design of a routing protocol for VANETs able to establish forwarding paths that fulfill bandwidth requirements. To this end, we study the possibility to use, in realistic VANET urban scenarios, the available bandwidth estimator (ABE) that was proposed and evaluated for IEEE 802.11-based MANETs in [9]. We have implemented in NCTUns [63] an extension of AODV that includes the ABE estimation [64]. ABE is used to assist the AODV routing protocol so that the established forwarding path satisfies the bandwidth required by the multimedia application. This extension is called AODV-ABE hereafter. Knowing that available bandwidth estimations are often weak regards to mobility, our simulation results show that AODV-ABE could be used in urban-VANETs where vehicles' speed is moderate.

The results of this chapter are supported by the articles "Available Bandwidth-aware Routing in Urban Vehicular Ad-hoc Networks" presented in the 76th IEEE Vehicular Technology Conference (VTC-Fall 2012) [64] and "Available Bandwidth Estimation in GPSR for VANETs" submitted in the 3rd ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet 2013) [65].

4.2 Quality of Service (QoS) provision as a challenge in VANETs

Safety, comfort driving and infotainment applications for passengers are some of the main services proposed for VANETs. Some services are critical, such as collision warning; other services need bandwidth, such as video-streaming services. QoS (Quality of Service) provisioning is a challenge in VANETs due to their special features, specially the high speed of the nodes, which result in frequent routing path disruptions.

In order to offer services over wireless ad-hoc networks with good performance, QoS mechanisms often require an estimation of available resources. In multihop ad-hoc networks, the estimation of the available bandwidth is a difficult task. Several proposals [9] [66] [67] have been presented to compute the available bandwidth on IEEE 802.11 wireless links and most of them have been evaluated in MANETs. For instance, ABE [9] combines channel monitoring to estimate each node's medium occupancy including distant emissions, probabilistic combination of these values to account for synchronization between nodes, estimation of the collision probability between each couple of nodes, and variable overhead's impact estimation. This mechanism only requires one hop information communication and may be applied without generating a too high additional overhead. RABE [66] (Retransmission-based Available Bandwidth Estimation) also considers in its estimation the bandwidth wasted by extra waiting time and medium occupancy due to retransmission. This estimation requires to compute the collision probability and the mean number of retransmission attempts. IAB [67] takes into account the common medium occupation periods between the two end nodes of each link and the independent occupations periods. They are computed thanks to the sensing busy state during which one end node senses the medium busy while its neighbour senses the medium idle. This computation assumes a uniform distribution of nodes in the network.

Current routing protocols in VANETs have difficulties to provide QoS. A QoS-aware routing protocol should guarantee satisfactorily a certain level of performance. This is often achieved through resource reservation and dedicated infrastructure. However, the dynamic and infrastructureless nature of VANETs makes it difficult to do resource reservation. Some actions to improve the performance in vehicular routing have been proposed, e.g., algorithms to estimate the time during which a route will remain connected [68]. The work in [69] presents a routing protocol to improve QoS in VANETs in terms of delay, response time and throughput. This scheme disseminates packets among those links that have longer expiration time. The routing selection and maintenance are based on the mobility of vehicles. A routing algorithm for achieving optimal QoS for highly dynamic VANETs is proposed in [70]. The proposal identifies optimal paths using the idea of next hop selection, considering parameters such as delay, packet loss and bandwidth.

Regarding routing protocols, the advantage of AODV [44] is its simplicity and widespread use. The main drawback is that AODV needs end-to-end paths for data forwarding, which is difficult to handle because in VANETs end-to-end paths break often due to the high speeds of vehicles. Other routing protocols use strategies like greedy forwarding and geographical routing [49] [71], but at the cost of greater complexity and increased delay. Nonetheless, for some multimedia applications that require a minimum bandwidth and short delay, AODV can perform well. In this chapter, we are considering smart city services where vehicles need to find quickly the closest access point (e.g. set in some intelligent traffic lights) for instance to send a short video clip of an accident to the ambulance unit, a picture reporting a traffic infraction or to retrieve a short video clip of the traffic conditions ahead. In this kind of applications, it is not necessary to establish long paths that last long, the communication must be quick and a minimum bandwidth should be provided.

Our proposal is similar to the works [68] [69] and [70], in the sense that it uses AODV as the basic operation to find routes and it includes algorithms to improve the performance of QoS parameters. Nevertheless, none of these works includes a real-time analytical scheme based on very few measurements to estimate the bandwidth, which is what we use in our proposal. The goal of this section is to evaluate the benefits of the AODV-ABE analytical tool to estimate the available bandwidth over a VANET urban scenario.

4.3 ABE: Available Bandwidth Estimation algorithm

In this section we summarize the main features of ABE (Available Bandwidth Estimation) proposed in [9] to estimate the available bandwidth in IEEE 802.11-based ad hoc networks. IEEE 802.11 is the standard adopted in VANETs [1] [4]. In particular, the IEEE 802.11p extension includes specific features for the physical layer (e.g. codification and frequency) to cope with the issues of high mobility nodes. The MAC layer in IEEE 802.11p is exactly the same as in IEEE 802.11. As ABE bases its estimation on the IEEE 802.11 MAC principle, we only consider IEEE 802.11 hereafter. For a full description of ABE, the interested reader can refer to [9].

4.3.1 Synchronization of idle periods

In ABE, each node estimates its idle time period by sensing the medium. The available bandwidth estimation of a wireless link in ABE uses the idle time periods of the emitter and the receiver of the link. However, for a communication to take place, emitter and receiver must be both idle. As there is no reason that emitters and receivers are always idle at the same time, ABE includes, in its estimation, the probability that two end nodes of a link be both idle at the same time. To this end, a uniform random distribution of the medium occupancy over an observation period is assumed. The basic analytical expression to estimate the available expected bandwidth $E(b_{(s,r)})$ in the wireless link formed by nodes s and r considering the overlapped synchronization periods is:

$$E(b_{(s,r)}) = T_s \cdot T_r \cdot C \tag{4.1}$$

where T_s is the idle time period at the sender side, T_r is the idle time period at the receiver side and C is the maximum medium capacity.

4.3.2 Collision and backoff mechanism

As the estimation of the idle periods synchronization is only probabilistic, collisions can still arise. This happens when a packet is emitted while the medium is not idle at the receiver's side. Such a collision triggers the binary exponential backoff mechanism. Collisions and a backoff increase impact the available bandwidth. ABE computes the collision probability from hello messages often used in routing protocols.

The packet collision probability for packets of m bits, p_m, is derived from the collision probability of *Hello Messages* (p_{hello}), in the following way:

$$p_m = f(m) \cdot p_{hello} \tag{4.2}$$

where $f(m)$ is a Lagrange interpolating polynomial obtained from simulation. The additional overhead introduced by the binary exponential backoff mechanism is computed as:

$$K = \frac{\text{DIFS} + \overline{\text{backoff}}}{T_m} \tag{4.3}$$

where T_m (in sec) is the time separating the emission of two consecutive frames, DIFS [72] is a fixed interval and $\overline{\text{backoff}}$ is the number of backoff slots decremented on average for a single frame.

Finally, by merging the different mechanisms that impact the available bandwidth, ABE estimates the available bandwidth on a wireless link as follows:

$$E_{final}(b_{(s,r)}) = (1 - K) \cdot (1 - p_m) \cdot T_s \cdot T_r \cdot C \tag{4.4}$$

4.3.3 ABE in routing protocols

AODV-ABE and **GPSR-ABE** are modifications of the basic routing protocols, AODV and GPSR respectively, that include ABE in their operation to estimate the available bandwidth on wireless links. Nodes periodically update their available bandwidth using the ABE mechanism with Equation (4.4). When a new source wants to send a packet to a destination, AODV-ABE floods a route request message (RREQ) to that destination by including the required bandwidth in the RREQ. Each intermediate node that receives the RREQ checks if there is enough bandwidth on the link from which it receives the RREQ. If this is the case, the RREQ is forwarded; conversely, the required bandwidth can not be satisfied and the RREQ is simple discarded. This allows us to establish a forwarding path that satisfies the required bandwidth, when such a path exists.

In GPSR, the selection of the next hop is done in a hop-to-hop way, if a new source wants to send a packet to a destination the node has to select the best next hop from its list of neighbours. Using ABE in this protocol, when the source selects the best next hop also checks if there is enough bandwidth on the links that form the forwarding path. If not, the source tries to find another neighbour that satisfies the required bandwidth.

4.4 ABE in VANET urban scenarios

This section presents some representative simulation results of the performance evaluation of the use of ABE in VANET urban scenarios. We compare the performance of AODV-ABE, GPSR-ABE, AODV and GPSR. The general simulation settings are given in Table 4.1. The propagation model employed in our simulation is the Two Ray Ground Model. IEEE 802.11p is not implemented in NCTUns yet. However, we use IEEE 802.11 since both have the same MAC operation. The only difference is that IEEE 802.11p improves the physical layer for high speeds, so we could expect even better results with IEEE 802.11p.

We test two urban scenarios:

- A scenario where vehicles remain static to show the potential benefits of AODV-ABE in the most favorable scenario compared to AODV.

- A scenario where vehicles move according to the mobility model generator Citymob [41]. This mobility model generator allows us to create realistic urban mobility scenarios where cars follow streets and respect traffic signals.

We have carried out several simulations for each scenario obtaining similar results. Also we present results of the evaluation using GPSR and GPSR-ABE to show that ABE can also be implemented in geographic routing protocols, which are more adequate that AODV in VANET scenarios. The urban scenarios have 40 nodes randomly positioned in the streets. The area of simulation is 1500 m x 1500 m with streets of 100 m per side and intersections of 40 m. At intersections, cars randomly can turn right, left or continue in the same direction. In the mobile scenarios the maximum speed of the vehicles are 50 km/h.

Three CBR flows are sent, with source and destination randomly selected. Each flow is composed of 1000-byte packets with a data rate of 800 kbps using a 11 Mbps medium capacity. We use CBR flows to have identical scenarios in all the protocols. Flow 1 starts at 0 sec. and ends at 200 sec.; flow 2 starts at 50 sec. and ends at 150 sec. and flow 3 starts at 0 sec. and ends at 100 sec.

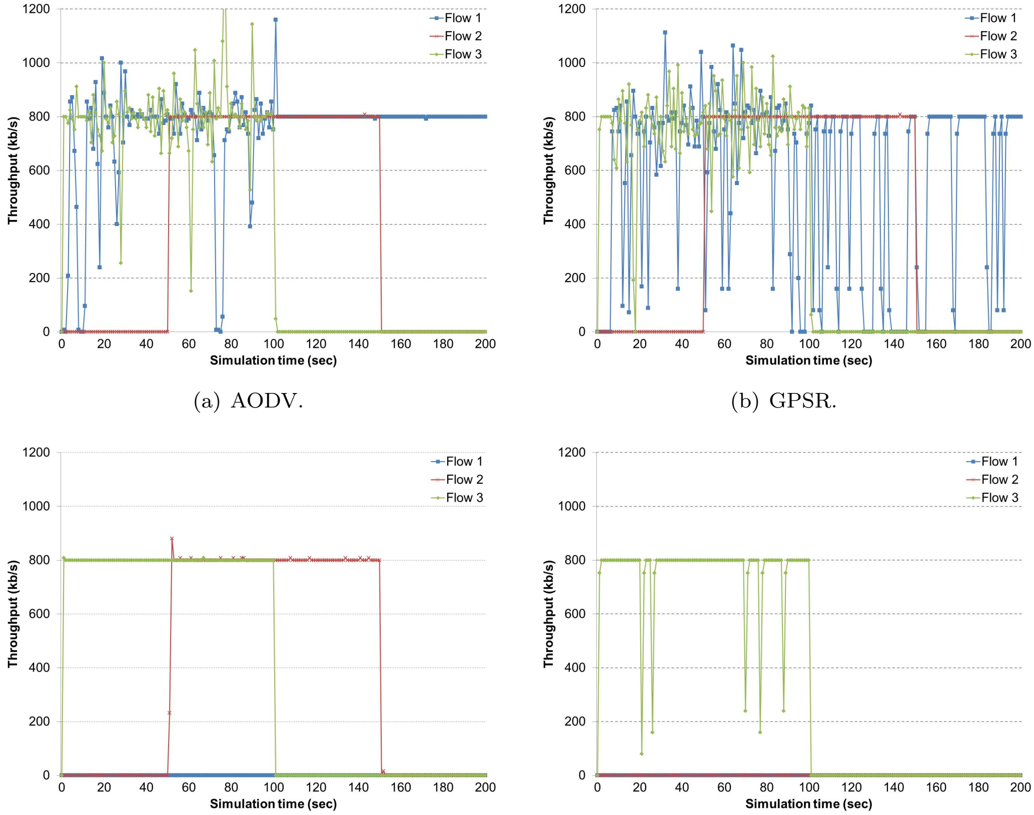
Table 4.1: Simulation settings in ABE evaluation.

Parameter	**Value**
Area	1500 m x 1500 m
Number of nodes	40
Max. nodes speed	50 km/h, 70 km/h, 90 km/h
Transmission range	250m
Sensing range	300m
Mobility model	Manhattan
Mobility generator	Citymob
MAC specification	IEEE 802.11b
Bandwidth	11 Mbps
Simulation time	1000 sec
Maximum packet size	1000 bytes
Routing protocol	AODV, AODV-ABE, GPSR, GPSR-ABE

4.4.1 Simulation results

As a first step during the analysis of the performance of protocols AODV, GPSR, AODV-ABE and GPSR-ABE, we use a static scenario. Results are shown in Fig. 4.1. Fig. 4.1(a) shows the throughput of the three flows when AODV is under evaluation. At 0 sec. flow 1 starts its transmission and obtains its target throughput (i.e., 800 kbps) while flow 3 begins at 0 sec. its transmission as well, and at the same time the network begins to be unstable. At 50 sec., flow 2 which also requires a throughput of 800 kbps starts and affects both flows 1 and 3 by getting lower throughput. At 100 sec. flow 3 ends and flows 1 and 3 start to achieve a better throughput (800 kbps for each one of them). Results are directly related to both positions (source and destination) that were selected randomly and this means that in every simulation three flows are chosen randomly so obviously each movement related to each connection will affect the result obtained. Fig. 4.1(b) shows the throughput of the three flows when GPSR is under evaluation. We observe that due to the hop-by-hop decision, the throughput is unstable. Both routing protocols achieve the best throughput possible taking into account that it is a VANET urban scenario as well as that there are buildings that totally block the signal knowing that to achieve the destination it needs a multihop forwarding scheme with the difference that AODV establishes an end-to-end path where GPSR a hop-by-hop forwarding decision.

When we use AODV-ABE (see Fig. 4.1(c)) we observe that flow 1 cannot establish a communication because the path did not achieve the required throughput. In the other hand, flow 2 and 3 obtained the required throughput and the communication is established taking into account QoS requirements. Fig. 4.1(d) shows the results using GPSR-ABE and we clearly observed that only flow 3 is established correctly. This behaviour is due to the hop-by-hop evaluation that only allows this communication



(a) AODV.

(b) GPSR.

(c) AODV+ABE.

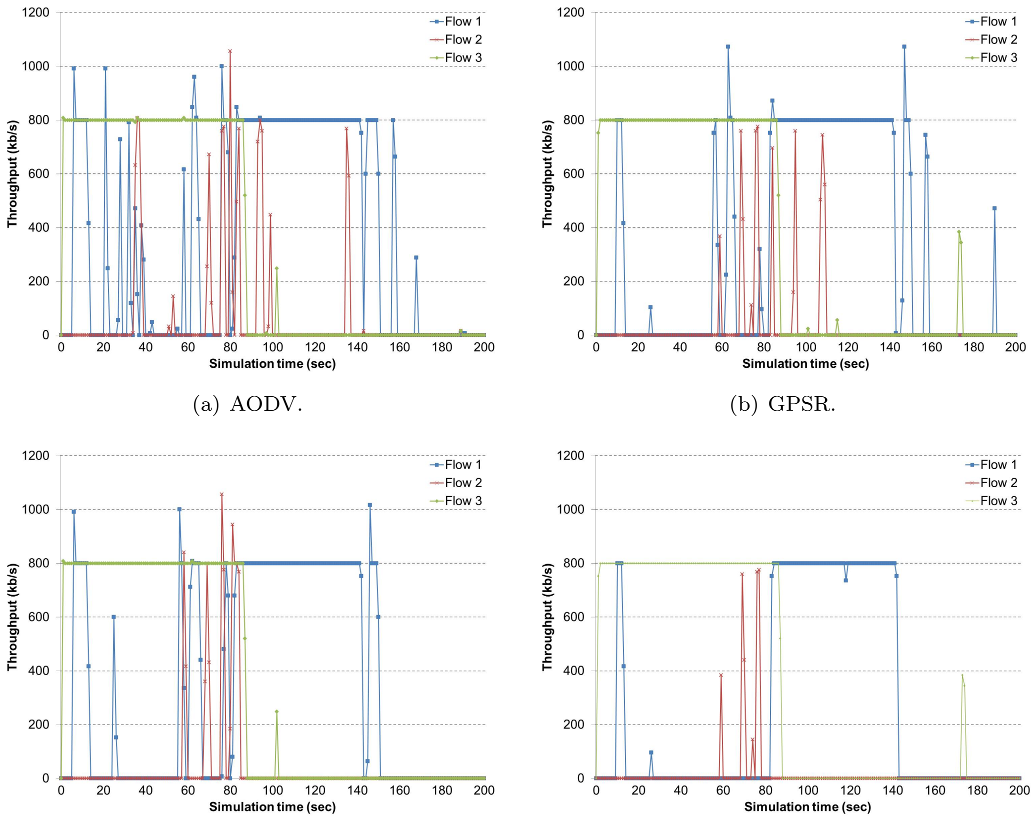
(d) GPSR+ABE.

Figure 4.1: Throughput of each flow in a fixed scenario.

to be established with the required QoS. GPSR-ABE drops more packets that usual because if one hop does not fulfil the requirements, packet is discarded.

Next we analyse the performance in a mobile scenario, 40 nodes with an average speed of 50 km/h in all vehicles, see Fig. 4.2. Similar to the previous settings, three communications are randomly selected (three nodes and three destinations). Fig. 4.2(a) and 4.2(b) show the throughput of the three flows when AODV and GPSR are evaluated respectively where we can clearly observe that the mobility affects the connection of the nodes producing variation in the throughput achieved knowing that without the use of ABE, communications are established at any available throughput.

When AODV-ABE (Fig. 4.2(c)) and GPSR-ABE (Fig. 4.2(d)) in a mobile scenario are evaluated we observe that flow start only if throughput of 800 kbps are achieved with a little exception and this is due to the mobility of the nodes that produces a



(a) AODV.

(b) GPSR.

(c) AODV+ABE.

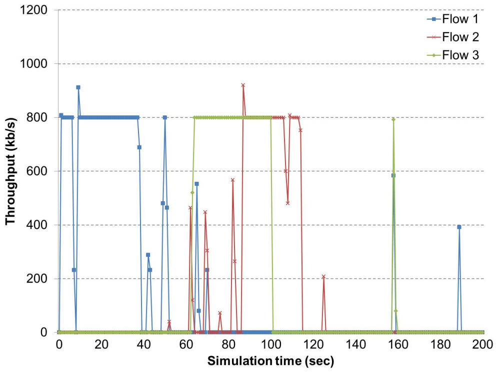
(d) GPSR+ABE.

Figure 4.2: Throughput of each flow in a mobile scenario at 50 km/h.

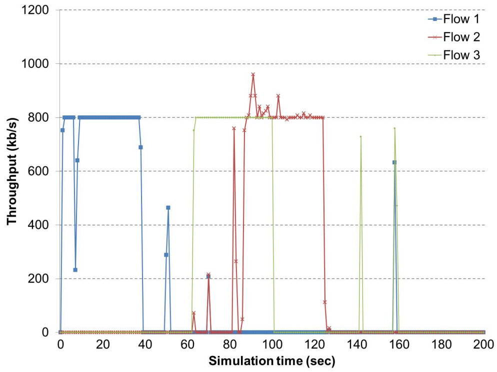
quickly changes in the topology.

Regarding each case, if we compare AODV (Fig. 4.1(a)) in a static scenario to AODV without ABE in a mobile scenario (Fig. 4.2(a)) we see that the three flows establish an end-to-end communication obtaining any throughput and available realizing at the same time that in mobile scenario results are more unstable due to the movement of the nodes that produces broken paths considering too that AODV use end-to-end paths.

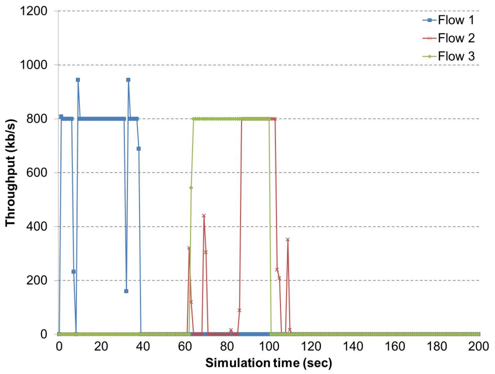
Comparing GPSR in a static scenario (Fig. 4.1(b)) to GPSR in a mobile one (in Fig. 4.2(b)), we see that in static mode it took higher throughput because in some moments of mobile scenario communication were not established. This behaviour is related to the topology changes in VANETs where GPSR tries to find the destination forwarding the packet hop-by-hop and if node does not find the next hop, packet is dropped.



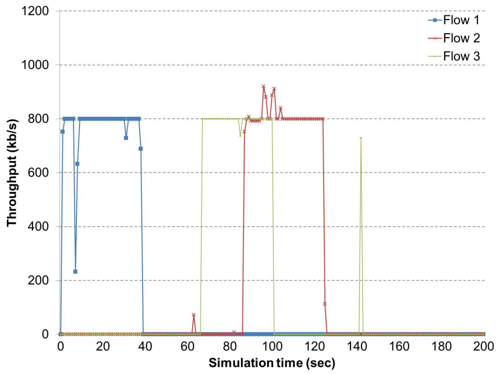
(a) AODV.



(b) GPSR.



(c) AODV+ABE.

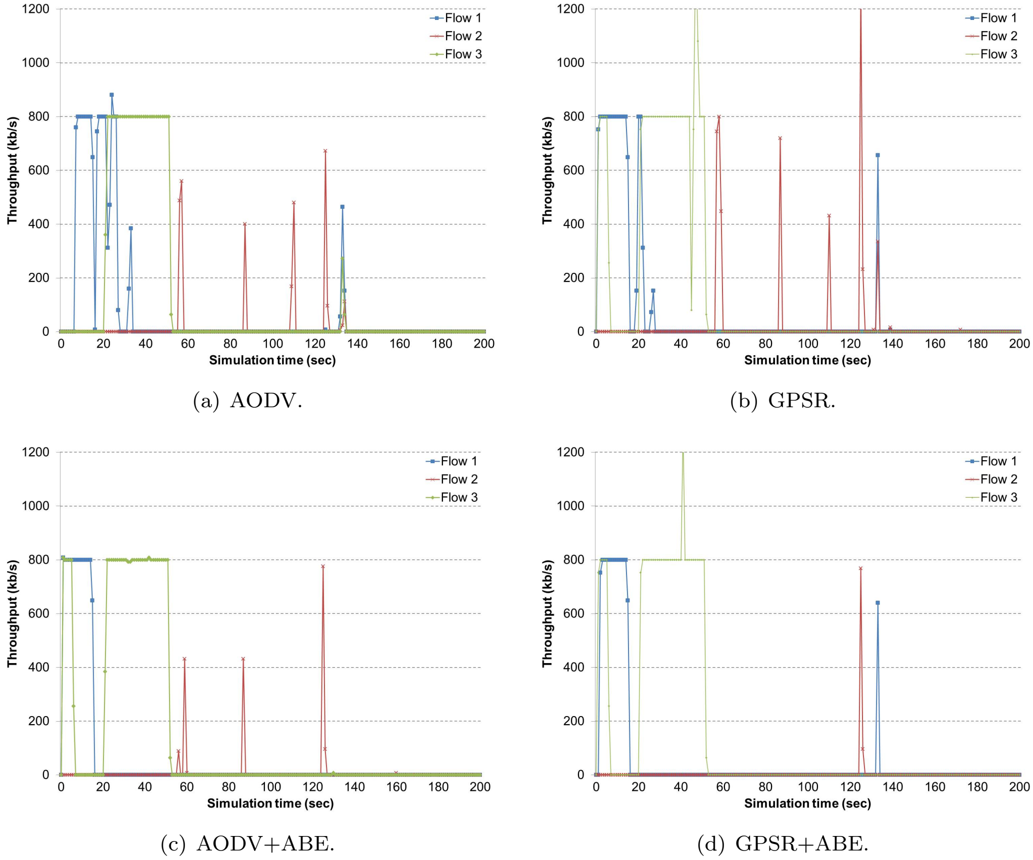


(d) GPSR+ABE.

Figure 4.3: Throughput of each flow in a mobile scenario at 70 km/h.

Using AODV-ABE in a static scenario (Fig. 4.1(c)) flows are only established if the necessary throughput is achieved. Knowing that the source and the destination are randomly selected, it could happen that there is no path found in order to reach the destination and this makes the communication uncompleted always and this is the case of flow 1 in Fig. 4.1(c). In the other hand, when the nodes are moving it could happen that a source can find forwarding nodes that meet the required throughput and could establish all flows with a certain QoS (Fig. 4.2(c)). In the same way this can happened with GPSR and GPSR-ABE in Figs. 4.1(d) and 4.2(d).

We compare the performance of the mobile scenario varying the average speed of the vehicles using 70 km/h and 90 km/h. Results are shown in Figs. 4.3 and 4.4 respectively making the same comparison as before between protocols AODV, GPSR, AODV-ABE and GPSR-ABE but specifically here we will see the effect of the speed in



(a) AODV.

(b) GPSR.

(c) AODV+ABE.

(d) GPSR+ABE.

Figure 4.4: Throughput of each flow in a mobile scenario at 90 km/h.

the establishment of the communication as well as the effect when it tries to offer QoS in VANETs.

Comparing Figs. 4.2, 4.3 and 4.4 it is easy to detect that as speed is increasing, the time that each flow remains established is decreasing and the reason is said before and is because the speed of the nodes produce quick changes in the topology which leads to have more broken links. Also because, the movement of nodes are generated by Citymob, generating a random movement to each node during all the time of simulation.

While we observe the functionality of ABE in the routing protocols, Figs. 4.3(a) and 4.3(b) show results of GPSR and AODV without ABE where it is possible to see that communication are established even if throughput offered does not fulfil the requirement. This occurs also in Figs. 4.4(a) and 4.4(b) but for less time because the high speed of vehicles (90 km/h) does not allow communication's time to be longer.

In the other hand, Figs. 4.3(c) and 4.3(d) where the protocols that have been evaluated are AODV-ABE and GPSR-ABE, we can clearly notice that communications are only established if the required throughput is achieved. The same conclusion is deduced from Figs. 4.4(c) and 4.4(d) where GPSR-ABE and AODV-ABE are evaluated with an average speed of nodes of 90 km/h. Here, we observe that the movement of the vehicles avoid having a long communications as well as the position of the sources and destinations that are selected randomly affect the behaviour of the entire communications.

We can deduce that ABE is a good algorithm to obtain a certain level of QoS in VANETs using geographic routing protocols.

4.4.2 Further adaptation of ABE for VANETs

After a deep analysis of the performance of the ABE algorithm in some routing protocols (GPSR, AODV) over VANETs, in particular after analysing the parameters considered by ABE (T_{idle} of the nodes, collision probability p_m and backoff effect k), see Equation (4.4), we conclude that the expression of ABE to estimate the packet collision probability (p_m) is the measure that provides greater discrepancy when compared to the values obtained from our simulations in VANET urban scenarios.

The reason is due to the function $f(m)$ used in the Equation (4.2) to estimate the packet collision probability that is included in the ABE algorithm. This $f(m)$ was obtained in [9] by computing the Lagrange interpolating polynomial, taking pairs of values of packet losses (p_m) and losses of hello messages (p_{hello}) from simulations of a fixed scenario with 4 nodes (2 of them hidden to each other) varying the packet size m. This fixed scenario is more likely to be found in MANETs, but it is quite different from vehicular scenarios where nodes follow streets in cities with buildings and respect traffic signs, so many other aspects should also be considered.

Because of this, we tried to improve the $f(m)$ function (Equation (4.5)), making an analysis of data of our own simulations in VANET urban scenarios.

$$f(m) = -5.65 \cdot 10^{-9} \cdot m^3 + 11.27 \cdot 10^{-6} \cdot m^2 - 5.58 \cdot 10^{-3} \cdot m + 2.19 \tag{4.5}$$

Also, we not only considered the packet size (m) as a variable, but also took into consideration other variables that are determinant in general in realistic vehicular scenarios. Therefore, we also considered nodes' density (N) in the scenario and the average speed of nodes (s). Our goal is to obtain a $f(m, N, s)$ function to be included in the equation of ABE to assist the routing protocol to take the best forwarding decision that minimizes packet losses.

We performed several simulations varying the packet size m=1000, 750 and 500 bytes. We used only these three packet sizes because it is the range of interest, since packet sizes higher than 1000 bytes produce a big amount of time occupancy of the medium each time it is accessed. Also, packet sizes lower than 500 bytes minimize the efficiency due to an increase of overhead, and also produce higher collisions since more packets need to be sent. Likewise, we varied the density of the scenario using a number of vehicles (N) between 40 and 180 nodes in each simulation. Finally, we used an average speed of the vehicles (s) between 30 km/h and 90 km/h, which are the common speeds in cities. From these combinations, we obtained the following analysis of packet losses depicted in Fig. 4.5.

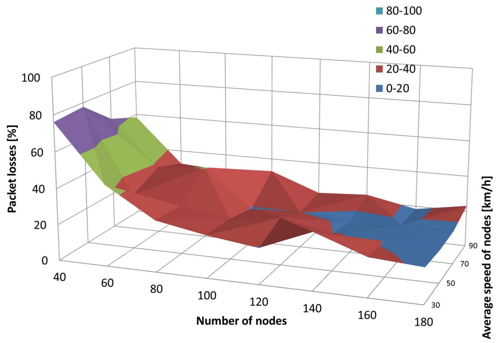
Fig. 4.5(a) shows the percentage of packet losses in an urban scenario where the packet size is m=1000 bytes. We can see that increasing the number of nodes, the percentage of packet losses decreases. This happens because when the number of neighbours increases, the sender node has more candidates to choose a next hop to forward the packets. The same happens with any average speed, i.e., increasing the speed (but in the range of interest) there are fewer losses. The reason is that at higher speeds there are new vehicles often so better candidates to choose a next forwarding node. However for much higher speeds the losses would increase due to link breakages. In Figs. 4.5(b) and 4.5(c) the same analysis is done, but using packet sizes of 750 and 500, byte respectively.

As we can see in Fig. 4.5, the packet size m is a parameter that has not noticeable effect in the results, which almost do not vary on m (for the range of sizes of interest that we have used). This is because a node in a VANET, i.e., a vehicle, has a high processing power so that packet losses are not much affected by the packet size. So, accessing to the medium to transmit a packet is a fast process. If the number of neighbours is not high, the percentage of collision will be low. The average speed of the nodes neither has a notorious impact in the packet losses (in the range of consideration between 30 km/h and 90 km/h). When the average speed is closer to 30 km/h the nodes use more often the buffer to store packets until they find a proper neighbour to forward them. When the nodes are faster (90 km/h), the sender can find a new neighbour faster or can get destination quickly to deliver the packet. This happens in case of sparse scenarios (around 40 or 60 nodes). In denser scenarios (around 120 nodes) normally there are enough neighbours and the transmission link is long enough to make the packet transmissions successfully.

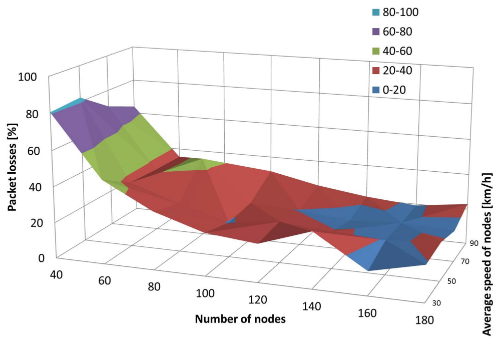
The metric that has more impact in the results in VANETs, is the density of nodes in the scenario. We can see that in scenarios with 100 or 180 nodes and with an average speed of 50 km/h the lower percentage of losses is obtained. This happens independently of the packet size (m) used. This result has sense, because if a node has enough neighbours in its transmission range, the possibility to forward the packets and select better neighbours is higher.

Taking into account the three variables of interest (number of nodes N in the scenario, speed of the nodes s and packet size m) for our scenarios, and having observed the effect of each parameter in the packet losses, the next step is to find an expression $f(m, N, s)$ to substitute the former $f(m)$ in the Equation (4.5) of ABE that fits better in vehicular scenarios instead of $f(m)$ designed for MANET scenarios, which were the scenarios for ABE in the original design [9].

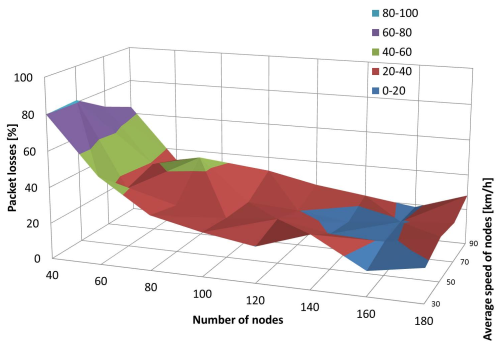
We made a multiple lineal regression [73] [74] with the results obtained from simulations, varying the three parameters N, s and m in a wide range of values of



(a) Scenario with packet size of m=1000 bytes.



(b) Scenario with packet size of m=750 bytes.



(c) Scenario with packet size of m=500 bytes.

Figure 4.5: Percentage of packet losses using original $f(m)$ with different packet size.

Table 4.2: Model summary[b].

R	R square	Adjusted R square	Std. error of the estimation
0.811[a]	0.658	0.646	0.3045352

a. Predictive variables: Constant, speed (s), number of nodes (N), packet size (m).
b. Dependent variable: p_m/p_{hello}.

interest. The software IBM SPSS 20[1] [75] was used. The resume of the results are shown in Table 4.2.

The values in Table 4.2 are defined as follow:

- R: Correlation coefficient: It shows the grade of relation between the observed values (losses) and the variables (s, N, m). It is a value between 0 and 1. Lower values indicate low or none relation between the predictive variables and the dependent variable.

- R^2: Determination coefficient: Measure of goodness of fit of a linear model. It is the proportion of the variation of the dependent variable explained by the regression model. R^2 takes values between 0 and 1. A small value indicates that the model does not fit the data well.

- *Adjusted* R^2: It is an optimistic estimation of the fit of the model to the measures.

- *Std. error of the estimation*: Standard deviation of the sampling distribution.

With the values of Table 4.2, we can conclude that our three predictive variables (speed s, nodes' density N and packet size m) explain well the 65.8% of the probability of packet losses. This conclusion is obtained from the second column in Table 4.2 (R^2=0.658) that gives the fit goodness of a linear model.

An analysis of variance of the regression (ANOVA) was made to determine if the model has statistical validity. The results are summarized in Table 4.3, which includes $sumofsquares$ (the sum of the squared deviations of each value with respect to the mean; this value measures the maximum dispersion of the data), *df* (freedom degree of the sample size, which is n=96 in our case), $meansquares$ (sum of squares/*df*) and F (ratio of two mean squares; this value helps to measure the variability of the data).

The results in Table 4.3 confirm that our model has statistical validity, since the significance (Sig.) is low than 0.05. A low value of significance (Sig.) indicates that the values are not random. This way, we can conclude that the model fits well with the simulation results using the parameters N, s and m.

[1] IBM SPSS Statistics provides univariate and multivariate modeling techniques to help users reach the most accurate conclusions when working with data describing complex relationships. These sophisticated analytical techniques are frequently applied to gain deeper insights from data used in disciplines such as medical research, manufacturing, pharmaceutical and market research.

Table 4.3: Analysis of variance ANOVA[a].

	Sum of squares	*df*	Mean square	F	Sig.
Regression	16.391	3	5.464	58.912	.000[b]
Residual	8.532	92	.093		
Total	24.923	95			

a. Dependent variable: p_m/p_{hello}.
b. Predictive variables: Constant, speed (s), number of nodes (N), packet size (m).

In Table 4.4 we show the statistic results of the regression: minimum, maximum, average and standard deviation of the whole measurements.

Table 4.4: Statistics of residuals[a].

	Minimum	Maximum	Average	Standard deviation	n
Predicted value	.164218	1.545047	.854633	.4153721	96
Residual	-.4327298	.79061570	.000	.2996882	96
Predicted value tip.	-1.662	1.662	.000	1.000	96
Residual	-1.421	2.596	.000	.984	96

a. Dependent variable: p_m/p_{hello}.

The model of multiple linear regression is given by $Y = \alpha + \beta_1 X_1 + \beta_2 X_2 ... + \beta_n X_n + \varepsilon$, where X's are the explanatory (or independent) variables and β are the parameters to estimate and measure the influence of the variables. The β parameters are also called regression coefficients. The α is the intercept (or constant). Finally, ε is called the error term, which captures all other factors which influence the dependent variable Y (assumed $E\varepsilon_i = 0$). These unknown values are obtained using the software IBM SPSS 20. The values of this regression are summarized in Table 4.5.

Table 4.5 includes the values to be implemented in the model (column called B, in red). We see the value of the constant is 1.9846 (that is α in the model) and then the value of the β's (-0.00007475, -0.008983 and -0.001428) respectively for each X's (i.e. m, N and s).

Also, in Table 4.5 we can see the value of significance (Sig., last column) of each value to be used (constant α, m, N, s). We can confirm that the constant α and the number of nodes N (number of vehicles in the scenario) have the higher influence, because both have obtained a significance lower than 0.05 (see last column of Table 4.5).

After this analysis we obtain the final expression for $f(m, N, s)$, shown in Equation (4.6).

$$f(m, N, s) = -0.00007475m - 0.008983N - 0.001428s + 1.9846 \quad (4.6)$$

This function $f(m, N, s)$ will substitute the former $f(m)$ in Equation (4.2) obtained

Table 4.5: Coefficients[a].

	Unstandardized coefficients B	Std. error	Standardized coefficients Beta	t	Sig.
Constant	1.9846	.163		12.185	.000
m	-0.00007475	.000	-0.030	-.491	.625
N	-0.008983	.001	-.808	13.245	.000
s	-0.001428	.001	.063	-1.028	.307

a. Dependent variable: p_m/p_{hello}.

in the original ABE [9] that relates the packet collision probability (p_m) with the collision probability of hello messages (p_{hello}).

Notice that p_{hello} is computed during simulation, so it will have different values for each scenario (with different values of N, m, and s). So in fact, p_{hello} is a value that depends on m, N and s. The final packet collision probability, $p_{m,N,s}$, is shown in Equation (4.7).

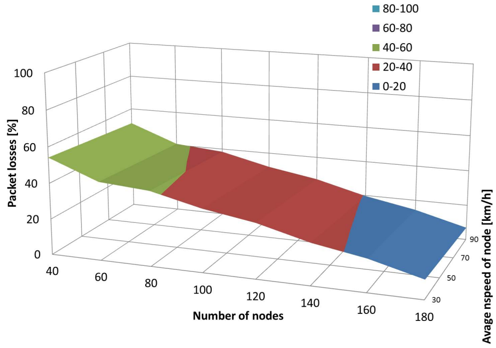
$$p_{m,N,s} = f(m, N, s) \cdot p_{hello}(m, N, s) \tag{4.7}$$

We compute the number of received hello messages and the number of expected hello messages, obtaining in that way an estimation of the collision probability of hello messages between both peers.

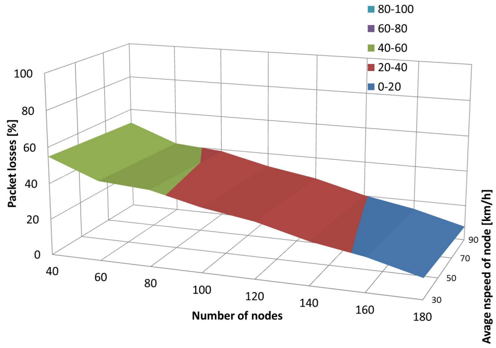
In Fig. 4.6 we depict the results of packet losses obtained with our new model (Equation (4.7)) evaluated for packets with m=1000, 750 and 500 bytes, respectively.

Finally, we compare the difference of the percentage of packet losses using our expression $f(m, N, s)$, see Equation (4.7), with the percentage of packet losses using the former expression $f(m)$ (using Equation (4.5)) We show Fig. 4.7 for different values of the average speed (s=50, 70 and 90 km/h, respectively) where we see the probability of packet losses obtained using different packets sizes m. The results probe that our new expression $f(m, N, s)$ gives results closer to simulation results than the original $f(m)$ used in ABE. The expression obtained from our lineal regression try to fit in the closest possible to the simulation results considering the three variables (average speed of nodes, density of the scenario and packet size). In Fig. 4.7 we can see that the original $f(m)$ (green line) shows higher average packet losses due only considers in the calculation the packet size and our results are very dependent of the mobility and density of our vehicular environments.

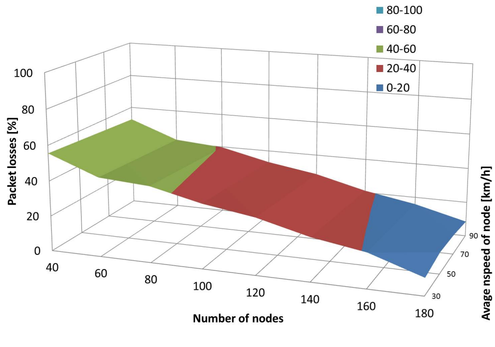
We can conclude that $f(m, N, s)$ gives a good approximation of the packet losses to the simulated results using several parameters of the urban scenarios in vehicular networks. This new function is used in a new routing protocol for VANETs in Chapter 5.



(a) Scenario with packet size of m=1000 bytes.

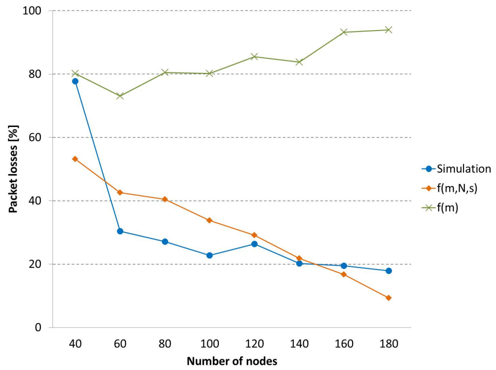


(b) Scenario with packet size of m=750 bytes.

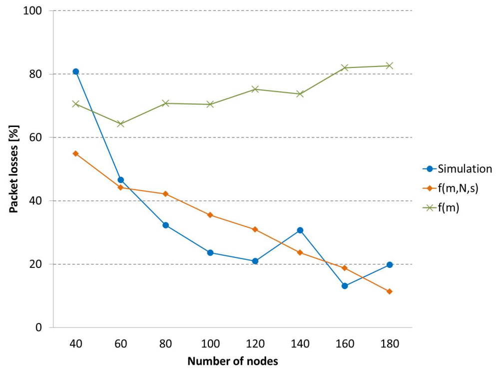


(c) Scenario with packet size of m=500 bytes.

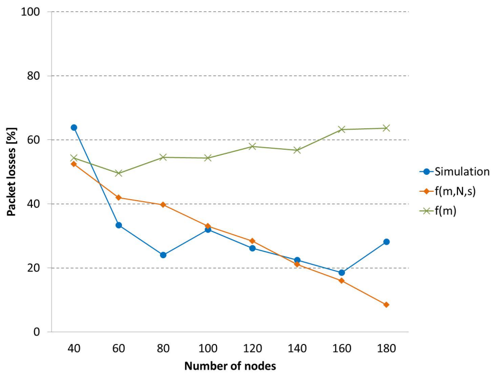
Figure 4.6: Percentage of packet losses using new model $p_{m,N,s} = f(m, N, s) \cdot p_{hello}(m, N, s)$ with different packet size.



(a) Packet size of m=1000 bytes and average speed s=50 km/h.



(b) Packet size of m=750 bytes and average speed s=30 km/h.



(c) Packet size of m=500 bytes and average speed s=90 km/h.

Figure 4.7: Percentage of packet losses comparing $f(m, n, s)$, $f(m)$ and simulation results.

4.5 Conclusions

In this chapter we have studied the possibility to use, in realistic VANET urban scenarios, the available bandwidth estimator (ABE) in the AODV routing protocol (called AODV-ABE) and in a geographic protocol like GPSR (GPSR-ABE) so that the established forwarding path satisfies the bandwidth required by the application. We have implemented AODV-ABE and GPSR-ABE in NCTUns and tested the performance of both protocols over urban VANETs by using the realistic traffic model generator Citymob.

Simulation results show that, with AODV-ABE and GPSR-ABE, flows can achieve the required throughput under fixed and mobile scenarios. Under high mobility, it is more difficult to establish the forwarding paths with a given throughput, but the performance of ABE is good and it is a good algorithm to provide a certain level of QoS in VANETs.

Also, we include a study of a new function $f(m, N, s)$ used in ABE to obtain the probability of packet collision based on the packet size, the density of the scenario and the average speed of the nodes. That enhances the original function $f(m)$ based only on the packet size. The new function improves the results in vehicular urban scenarios.

Chapter 5

MMMR: A Multimetric, Map-aware Routing Protocol

5.1 Introduction

Vehicular Ad hoc Networks (VANETs) [1] [4] are an emerging area of wireless networking that facilitate ubiquitous connectivity among smart vehicles through Vehicle-to-Vehicle (V2V) communications and between vehicles and the city or the road infrastructure through Vehicle-to-Roadside (V2R) communications. This emerging technology field aims to improve the safety of passengers, to alleviate traffic flow, to reduce pollution and to enable in-vehicle entertainment applications for passengers. Safety applications can reduce accidents by providing traffic information to drivers, such as collision warning, road surface conditions or state of the traffic flow. Moreover, passengers could use the available infrastructure of the city to connect to the Internet for entertainment applications [11].

The growing interest in this technology is an incentive for car manufacturers, the research community and governments who day after day increase their efforts towards creating a standardized platform for vehicular communications. The unique characteristics and special requirements of VANETs generate challenges for the research community. To address these challenges in both safety and comfort-oriented applications, there is a pressing need to develop new routing protocols specially designed for VANETs able to work well either under sparse or dense traffic conditions. In this chapter a new proposal of a routing protocol for VANETs is presented which considers several metrics to select the best next forwarding node for each packet in each step towards its destination. Simulation results show the benefits of our protocol compared to other proposals under different network conditions.

The results of this chapter was submitted to the Computer Communications journal in the paper "A Multimetric, Map-Aware Routing Protocol for VANETs in Urban

Areas", *submitted* [76].

5.2 Multimetric to select the best next forwarding node

Traditional traffic management systems are based on centralized infrastructures where cameras and sensors implemented along the roadside collect information about the vehicle density and the traffic state. This data is sent to a central unit that processes it and takes appropriate decisions. This type of framework is very costly in terms of deployment and is characterized by a long time to process information.

With the rapid development of wireless communication technologies of the last years, a new decentralized architecture based on Vehicle-to-Vehicle communications has raised an interest from car manufacturers, the research community and governments. Vehicular Ad hoc Networks are a specific type of Mobile Ad hoc Networks (MANETs) [4] where nodes are vehicles. The road-constrained characteristics of these networks, the high mobility of the vehicles, their unbounded power source, and the presence of roadside wireless infrastructures make VANETs an important research topic. The main purpose of VANETs is to be a platform that can support intelligent inter-vehicle communication improving traffic safety, although they are also useful for traffic management and other services, e.g. Internet access.

The presence of city infrastructure in emerging smart cities has an important impact on urban communications. In some applications one must find a route to the closest access point (AP), e.g. connecting to the Internet. In a city with advanced wireless infrastructure deployed, it would take only a few hops to reach the nearest AP under day-traffic conditions. Roadside access points should be placed in special locations, such as on traffic lights since they are well positioned to act as traffic routers. They already form a traffic grid, usually located where traffic is most intense and are equipped with power supply and directly maintained by local municipalities. For instance, [77] proposes a priority intersection control scheme in a self-organized manner, so that smart traffic lights detect the presence of emergency vehicles and assign priority to the emergency vehicles at intersections. The goal is to provide a "*green-wave*" signal display for the emergency vehicles that makes vehicles obey the traffic lights and therefore accidents can be avoided.

Several proposals of routing protocols for VANETs have been presented. Research works claim that the best routing protocols for VANETs are those that use geographic routing, which are based on the knowledge of the instantaneous locations of nodes [78].

GPSR (Greedy Perimeter Stateless Routing) [49] is a well-known geographic routing protocol specially designed for VANETs. It forwards packets to the neighbour node which is closest to destination following a hop-by-hop scheme. GPSR uses two different techniques to forward packets: *greedy forwarding*, which is used by default, and *perimeter forwarding*, which is used whenever greedy forwarding cannot be used. Since nodes require knowing their neighbours' positions, periodically each node transmits a hello message containing its own identifier (e.g. IP address) and its position. Several proposals that improve GPSR have been presented in the literature. The authors in [52] proposed Movement Prediction-based Routing (MOPR), which improves the routing process of GPSR by selecting the most stable route in terms of lifetime with respect to the movement of vehicles. In [54] an algorithm was proposed that modifies GPSR and exploits information about movement to improve the next forwarding node decision. The authors use information about position, moving direction and speed to make routing decisions. The proposed protocol was compared to GPSR in a highway setting, showing improvement. The Advanced Greedy Forwarding (AGF) [60] improves the performance of GPSR since its forwarding technique is more fault-tolerant than the traditional greedy forwarding used in GPSR.

Recently, some proposals of routing protocols for VANETs that include several metrics have been presented. The use of alternative metrics in VANETs in addition to the classic distance has shown notable benefits. For instance, the trajectory of the vehicles is used in [52] and [57]. The authors in [53] propose the Improvement GPSR routing protocol (I-GPSR), which incorporates distance, vehicle density, moving direction and vehicle speed to take packet forwarding decisions. A new data forwarding mechanism was presented in [57] that uses a store-carry-forward scheme besides the position information and moving direction of the nodes.

Nevertheless, none of the existent proposals takes the available bandwidth into account as a metric to take forwarding decisions. The reason could be that obtaining a fairly simple but accurate model to calculate the available bandwidth in VANETs is a difficult task. Our proposal includes several metrics to optimize the selection of the next forwarding node in a geographic-based protocol. These metrics are vehicle density, trajectory, distance to destination and available bandwidth. The trajectory of a node consists of its moving direction and its speed, which are used to estimate how fast a node gets near to or goes away from destination. Then, we weight those four metrics into a single multimetric score. Furthermore, we evaluate the performance of each single metric compared to the global multimetric value and also to some combination of them.

5.2.1 Motivation

In a VANET, nodes are vehicles that move along roads, potentially at high speed, following transit rules, direction of streets, respecting traffic lights and also the presence of buildings and other vehicles. The vehicle density in VANETs constantly changes depending on the area and the time of the day, so it is difficult to establish and maintain end-to-end communication paths between sources and destinations as it is traditionally done in MANETs. Several routing protocols have specially been proposed for VANETs based on geographic information. Nonetheless, a proper data forwarding mechanism is still needed to cope with the special constraints of VANETs, e.g. the high node speed and the dynamic topology with variable node density.

We propose a new routing protocol for VANETs in urban scenarios that we call MMMR (Multimetric, Map-aware Routing protocol). MMMR seeks to improve the next forwarding node decision based on four metrics which are the distance to destination, vehicle density, vehicle trajectory and the available bandwidth. We weight the four metrics to finally obtain a multimetric value associated with each neighbour node that is a candidate for next forwarding node. The scheme is self-configured and able to adapt to the changing vehicle density in real time.

In our proposal we can distinguish five processes: routing, map-aware capability, signalling, evaluation of metrics and forwarding decision. We explain each one in the following.

5.2.2 Routing

The forwarding decision included in our routing proposal MMMR uses the same criteria as the original GPSR [49]. It consists in choosing the neighbour located nearest to destination. Besides, it also considers two new improvements of the original process.

First, our proposal tackles the important issue of deciding which neighbours are actually reachable. This feature is of paramount importance to determine if a neighbour in the list could be a good forwarding node. The accurate information about the current position of a neighbour has a strong impact on the routing performance, because knowing this information makes the node aware of which neighbours are reliable to act as next forwarding nodes. At the same time, it avoids sending packets to an unreachable node, e.g. because it is behind a building.

Secondly, an important drawback of GPSR is the implementation of *perimeter forwarding*, because it is not clear when the algorithm switches its mode to greedy forwarding again. In addition, mobility can induce routing loops while using the *perimeter mode* [62]. To avoid these problems caused by perimeter forwarding, our proposal stores packets in a buffer when there is no neighbour that satisfies all the requirements needed to be a *next forwarding node*.

If at least one of the two conditions (i.e., being actually a reachable neighbour and being closer than the current carrier node to destination) required to be the next hop is not satisfied, then packets are stored in a local buffer. If the buffer gets full, packets are dropped.

MMMR tries to forward the packets stored in the buffer periodically, while it looks for a proper forwarding node. This period of time was set to 1 second, since this value is frequent enough to detect quickly any topology change. For each destination, packets are stored in order of arrival and sent in the same order, according to a FIFO scheme.

Packets are stored in the buffer and the node periodically looks for a neighbour that can satisfy the requirements to be the next forwarding node. Every period of time (1 second) the buffer looks for a new node candidate. If a candidate fulfills the requirements, the stored packets are forwarded to that node.

In addition to these two improvements, the next forwarding node decision is based on the combination of four metrics, detailed in Section 5.2.5.

5.2.3 Map-aware capability

An important issue that one should face trying to design a routing protocol for VANETs in urban scenarios is the presence of obstacles such as buildings, trees and other obstacles that can be found in the cities. Greedy forwarding in GPSR is often restricted because direct communication between nodes may not exist due to an obstacle. We include in our proposal a map-aware capability which focuses on two important enhancements: a) It takes into account the presence of buildings in the next forwarding decision and b) it selects the best way to manage the local buffer.

The presence of obstacles, such as buildings, are analyzed using vehicular location. If the straight line between the current vehicle position and the next vehicle position is blocked by any rectangular area representing a building, then from the vehicle driver's viewpoint, the retrieved destination vehicle should not be seen.

Three conditions must be verified, i.e., actually being in coverage range, having less distance to destination and being in LOS (Line of Sight). If the candidate fulfills all three requirements, packets are forwarded to that chosen candidate; otherwise they are stored in the local buffer of the current carrier node.

Using this building-aware scheme, if neighbours are out of LOS, packets are stored in the buffer. It is important to mention that although the building-aware scheme could be implemented without buffer, it would be pointless because without buffer it would be more difficult to quickly find a next forwarding node that satisfies these requirements. As a result, packets would be dropped and packet losses would increase, see Section 3.3.

5.2.4 Signalling

MMMR, as most geographic routing protocols, requires nodes to periodically send signalling messages to announcing their presence to the neighbours in transmission range. To obtain precise location information about each node, without introducing extra overhead, new fields were added in those hello messages (HM) for the exchange of information between neighbours. The new format of hello messages is presented in Table 5.1, and they include these new fields:

- **ID**. A 4-byte field with the identifier of each node.
- **Position**: This field is divided into 20 bits for latitude (l_x) and 20 bits for longitude (l_y) that represent the geographic position of each node. Each set of 20 bits is also divided into 1 bit for direction (north or south for longitude; east or west for latitude), 7 bits for grade, 6 bits for minutes and 6 bits for seconds.
- **Velocity**: A 2-byte field that uses 1 byte for speed in axis x (v_x) and 1 byte for speed in axis y (v_y). Each node calculates its own speed from two consecutive position points taken at times t_1 and t_2:

$$v_x = \frac{x_2 - x_1}{t_2 - t_1} \qquad v_y = \frac{y_2 - y_1}{t_2 - t_1}. \tag{5.1}$$

Table 5.1: New format of hello messages (HM).

ID	l_x	l_y	v_x	v_y	S	t_{idle}	ρ
32 bits	20 bits	20 bits	8 bits	8 bits	16 bits	8 bits	8 bits

- **Antenna sensing (S)**: 1 byte to express the antenna sensing used by the node in dBm.

- **Idle time (t_{idle})**: Each node calculates the units of time that spends without sending nor receiving data since the last HM sent. This value is represented in 1 byte. That is, t_{idle} measures the amount of time the node is idle between two consecutive hello messages.

- **Density (ρ)**: 1 byte to represent the number of neighbours within transmission range at the moment of sending the current hello message.

When a node receives a hello message from a neighbour in transmission range, the node stores the moment of reception and updates its neighbours list with all the values shown in Table 5.1. This is done following the conditions shown in algorithm 4. If a hello message is received from a neighbour already registered in the neighbours list, the information of this neighbour is just updated (lines 1-2 from Algorithm 4). To keep the neighbours list updated and use only nodes that actually are in transmission range, nodes remain in a neighbours list during 2 times the interval between consecutive hello messages.

When a node receives a hello message from a new neighbour (a neighbour not yet registered in the list), it has first to check if this is a stable node before adding it in the neighbours list. This means that hello messages have to be received with a power higher than the antenna sensing plus a security margin (lines 4 to 8). We set this security margin to 1 dB, since we observed from simulation results that this was a proper value. If this condition is not fulfilled, that neighbour will not be included in the neighbours list (line 7) since this node probably is around the border line of the transmission range. The sending period of hello messages could be higher to obtain more accuracy in the composition of the neighbours list, Although a higher signaling traffic could produce an increase in packet collisions. By default, the sending period of HM is set to 1 second.

The neighbours list includes the data sent in hello messages (see Table 5.1) and the data shown in Table 5.2. For each neighbour i, we store the moment when the last hello message arrived (*Last HM moment* in Table 5.2). This is done to estimate the future position of that neighbour node. Also, we store the moment when the first hello message arrived (*First HM moment*) and the total number of hello messages received (*No. HM*). These values will be used to estimate the available bandwidth using a metric explained in the next section.

Algorithm 4 . Updating the neighbours list.

Require: A new hello message received with these parameters: id, l_x, l_y, v_x, v_y, S, t_{idle}, ρ.

if (Neighbour is already in the neighbours list) **then**
  Update neighbour information
else
  if (ReceptionPower $\geq$ Antenna sensing + 1 dB) **then**
    Add node in the neighbours list
  else
    Ignore hello message
  end if
end if

Table 5.2: Extra data per node in the neighbours list.

Neighbour i	Last HM moment	First HM moment	No. HM
32 bits	8 bits	8 bits	8 bits

5.2.5 Evaluation of metrics

In this section we detail each one of the four metrics included in our multimetric algorithm MMMR, which is a geographic routing protocol based on hop-by-hop forwarding decisions. The use of these metrics is a way to improve the choice of the next forwarding node. The four metrics considered are the distance to destination, the trajectory of the vehicles, the node density and the available bandwidth. They are described in the following.

Distance: The typical goal of most geographic routing protocols is to send packets hop-by-hop to their destination so that the next forwarding hop is the neighbour which is closest to destination. These kind of protocols know geographic information of every node in the scenario. Each vehicle knows its own position and also the position of destination. So it is usually assumed that the position of the packet's destination and the positions of the next hop candidates are sufficient to make proper forwarding decisions. We also use the distance (d) to destination as a metric to evaluate each neighbour in our proposal. We obtain this information from the fact that senders know the destination position (x_D, y_D) and also each neighbour includes in hello messages its own position. With the position (x_i, y_i) of each neighbour i, we can obtain the Euclidian distance using Equation (5.2) for each node (i) to destination (D).

$$d_i(i, D) = \|\vec{x}_i - \vec{x}_D\| = \sqrt{(x_i - x_D)^2 + (y_i - y_D)^2} \tag{5.2}$$

We use Equation (5.3) to compute the metric of the distance, $u_{1,i}$, for each neighbour node i. d_i is the distance of each neighbour i to destination and d_{ref} is a reference distance above which losses increase notably faster. This d_{ref} is obtained from simulations where we evaluated the performance of a fixed node set in different distances from the AP (access point). The results are presented in Fig. 5.1 where we can see that d_{ref} is around 1998 m in our urban scenario. Notice that for a transmission range of 250 m such a path of almost 2000 m would take around 8 hops. α is an attenuation factor that equals 0.77 after a mathematical regression using the results of the same experiments referred before and shown in Fig. 5.1.

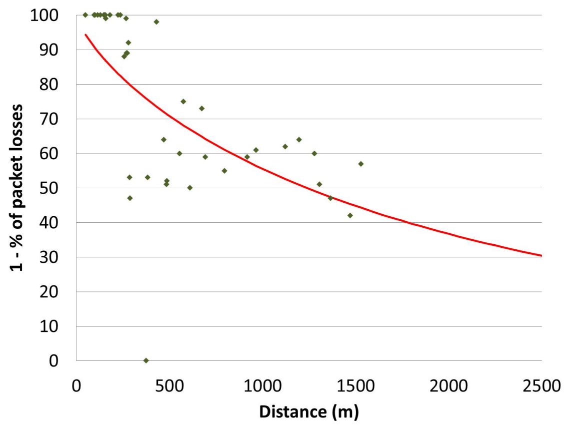


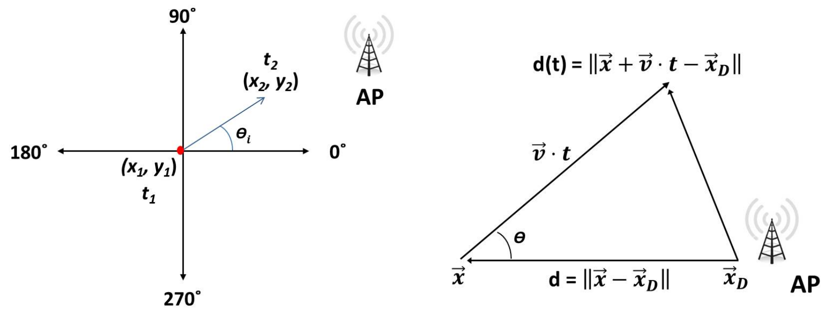
Figure 5.1: Relation between distance to destination and packet losses.

In this case, a shorter value of the distance d_i the better, because we prefer a neighbour as close as possible to destination. We use a negative exponential function to penalize drastically those neighbours with bad values in this metric. That means that the best forwarding node will get a score notably better than the others. This way, we highlight those good candidates so that they have more chances to be selected as next forwarding nodes.

$$u_{1,i} = e^{-\left(\frac{d_i}{d_{ref}}\right)^{\alpha}} \tag{5.3}$$

Trajectory: An important issue in VANETs is the accurate knowledge of the trajectory of vehicles. We consider the trajectory as a comparison of the future distance with to the current distance. A communication link in a VANET remains operative during a short time due to the high speed of the vehicles. If a geographic protocol did not consider the moving direction of nodes, the current node could take wrong forwarding decisions based only on the distance and send packets to vehicles that were actually going away from destination. Therefore, packet losses could increase as a consequence. For that reason, taking into account the moving direction of vehicles is an important feature in VANETs.

We obtain the trajectory metric $u_{2,i}$ of node i using the future distance $d(t)$ to destination of that node, where $d(0) = d$. We compute the $u_{2,i}$ value using



(a) (b)

Figure 5.2: Trajectory towards the Access Point (AP) from two consecutive geographic positions.

Equation (5.4) where $\Delta_d(t)^\alpha = d(t)^\alpha(t) - d^\alpha$ is the variation of the metric of distance (u_1) in a time t and the one will be derived later. The distance $d(t)$ is computed by estimating the future position of that vehicle using its speed according to Equation (5.5). The speed of the node, $\vec{v_i}$, helps us to give a higher score to nodes that sooner will be closer to destination (AP). The idea is that with higher speed, nodes may arrive sooner to destination since given that the distance to destination decreases.

$$u_{2,i} = e^{-\left(\frac{\Delta_d(t)}{d_{ref}}\right)^\alpha} \tag{5.4}$$

$$d(t) = \parallel \vec{x} + \vec{v_i} \cdot t - \vec{x}_D \parallel \tag{5.5}$$

$d(t)$ is an estimation of the future position of the node i in the time t, $(x_1,\ y_1)$ and $(x_2,\ y_2)$, as it is depicted in Fig. 5.2(a). v_i is the average speed of the evaluated neighbour i with respect to destination and computed from two consecutive positions, $\vec{x}$ and $\vec{x}_D$ are the neighbour and destination positions, respectively, see Fig. 5.2(b) ($\| \cdot \|$ refers to the module function of a vector).

Again, the use of an exponential function helps us to emphasize good nodes compared to the others. This way, a better qualification in $u_{2,i}$ is obtained if the node presents a faster decrease of its distance to destination.

Then, using a Taylor approximation in the estimation of the future position $d(t)$, we obtain Equation (5.6) where $O(t^2)$ represent the upper order terms.

$$d(t)^\alpha \quad = \quad d(0)^\alpha + \frac{d}{dt}d(t)^\alpha\Big|_{t=0} \cdot t + O(t^2) \tag{5.6}$$

In order to facilitate the calculation we write Equation (5.6) in terms of the well known expression $d(t)^2$ (i.e. with $\alpha = 2$) and we obtain $\frac{d}{dt}(d(t)^2)^{\frac{\alpha}{2}}$

$$\begin{aligned} d(t)^2 &= \parallel \vec{x} + \vec{v} \cdot t - \vec{x}_D \parallel^2 \\ &= \parallel \vec{x} - \vec{x}_D \parallel^2 + 2\langle \vec{x} - \vec{x}_D, \vec{v} \rangle t + \parallel \vec{v} \parallel^2 \cdot t^2 \end{aligned} \tag{5.7}$$

where $\langle \cdot \rangle$ refers to the scalar product. Notice that comparing Equation (5.7) to the Taylor approximation in Equation (5.6) where $d(0)^\alpha = \parallel \vec{x} - \vec{x}_D \parallel^\alpha$, we obtain

$$\frac{d}{dt} d(t)^2 \bigg|_{t=0} = 2\langle \vec{x} - \vec{x}_D, \vec{v} \rangle \tag{5.8}$$

Applying the chain rule in $\frac{d}{dt}(d(t)^2)^{\frac{\alpha}{2}}$ yields

$$\frac{d}{dt} d(t)^\alpha = \frac{\alpha}{2}(d(t)^2)^{\frac{\alpha}{2}-1} \cdot \frac{d}{d(t)} d(t)^2 \tag{5.9}$$

At $t = 0$ we have $d(t) = d$ and $\frac{d}{dt} d(t)^2 \big|_{t=0} = 2\langle \vec{x} - \vec{x}_D, \vec{v} \rangle$.
Hence,

$$\frac{d}{dt} d(t)^\alpha \bigg|_{t=0} = \frac{\alpha}{2} d^{2\left(\frac{\alpha-2}{2}\right)} \cdot 2\langle \vec{x} - \vec{x}_D, \vec{v} \rangle \tag{5.10}$$

Let θ be the angle between the vectors $\vec{x} - \vec{x}_D$ and $\vec{v}$, see Fig. 5.2(b). On account of the fact that $\langle \vec{x} - \vec{x}_D, \vec{v} \rangle = d \cdot \|\vec{v}\| \cdot \cos\theta$,

$$\begin{aligned} \frac{d}{dt} d(t)^\alpha &= \alpha \cdot d^{\alpha-2} \cdot d \cdot \parallel \vec{v} \parallel \cdot \cos\theta \\ &= \alpha \cdot d^{\alpha-1} \cdot \parallel \vec{v} \parallel \cdot \cos\theta \end{aligned} \tag{5.11}$$

Replacing (5.11) in (5.6) we conclude

$$\begin{aligned} d(t)^\alpha &= d^\alpha + \alpha \cdot d^{\alpha-1} \cdot \parallel \vec{v} \parallel \cdot \cos\theta \cdot t \\ \Delta_d(t)^\alpha &= \alpha \cdot d^{\alpha-1} \cdot \parallel \vec{v} \parallel \cdot \cos\theta \cdot t \end{aligned} \tag{5.12}$$

Equation (5.12) can be divided into two parts: the current distance d^α and the future position ($\Delta_d(t)^\alpha = \alpha \cdot d^{\alpha-1} \cdot \parallel \vec{v} \parallel \cdot \cos\theta \cdot t$). Notice that $d(t)^\alpha$ includes the current position (d^α), which is already considered in the metric of the distance ($u_{1,i}$). Notice that the exclusion of d^α in the trajectory metric is due to avoid dependencies between the $u_{1,i}$ and $u_{2,i}$ metrics in the final expression of the multimetric score, obtaining as a final equation of the trajectory:

$$u_{2,i} = e^{-\left(\frac{\alpha d^{\alpha-1} \|\vec{v}\| \cos\theta}{d^\alpha_{ref}}\right)} \tag{5.13}$$

Due to the exponential behavior of metrics $u_{1,i}$ and $u_{2,i}$, we decided to use exponential functions also to define the metrics of density $u_{3,i}$ and available bandwidth $u_{4,i}$. This way we avoid to have a too much influence of metrics $u_{1,i}$ and $u_{2,i}$ in the final value of the multimetric score. Because this both metrics obtain high values that could affect the final score.

Density: It is computed as the number of vehicles in the neighbours list of each node at the moment of sending the current hello message, divided by the transmission range. The neighbours list is composed by vehicles in transmission range that send packets with enough power to be considered stable neighbours. Each node computes the density of nodes ρ_i and includes it in the next hello message.

The algorithm gives a higher score when the node has a higher value of the density of nodes ρ_i, by using Equation (5.14). Nodes with a denser area in the transmission range will have more possibilities to forward the packet to a better next node. This is true until reaching a maximum traffic density, above which the high number of vehicles in the surrounding area of each node increases the collisions frequency.

$$u_{3,i} = e^{-\frac{1}{\rho_i}} \tag{5.14}$$

Available bandwidth: Multimedia services (e.g. video streaming) require a given amount of network resources to run correctly. To provide QoS with our proposal, we include an estimator of the available bandwidth in VANETs based on a previous approach developed for IEEE 802.11 networks called available bandwidth estimator (ABE) developed in [9]. We evaluated ABE for VANETs in [64] and improved its operation further in [65]. The ABE as a metric is used by our forwarding decision algorithm to choice the best next node.

In the following, we summarize the ABE operation to estimate the available bandwidth in a link between two nodes. A complete explanation can be found in [9]. Each node estimates its percentage of idle time by sensing the common wireless medium. This value is included in its hello messages. The available bandwidth estimation of a wireless link in ABE uses the idle times of the emitter (T_s) and the receiver (T_r) of a link of capacity C. ABE computes the collision probability of the hello messages, named p_{hello}. The packet collision probability of packets of m bits, named p_m, is derived from the collision probability of the hello messages using Equation (5.15).

$$p_m = f(m) \cdot p_{hello} \tag{5.15}$$

The function $f(m)$ is used in equation (5.15) to estimate the packet collision probability that is included in the ABE algorithm. This $f(m)$ was obtained in [9] by computing the Lagrange interpolating polynomial, taking pairs of values of packet losses (p_m) and losses of hello messages (p_{hello}) from simulations. The result is shown in Equation (5.18).

The additional overhead introduced by the binary exponential backoff mechanism was computed using Equation (5.16)

$$K = \frac{\text{DIFS} + \overline{\text{backoff}}}{T_m} \qquad (5.16)$$

where T_m (in sec.) is the time separating the emission of two consecutive frames, DIFS [72] is a fixed interval and $\overline{\text{backoff}}$ is the number of backoff slots decremented on average for a single frame. Finally, by merging the different mechanisms that impact the available bandwidth, the sender estimates the available bandwidth ABE_i on each neighbour' wireless link using Equation (5.17) [9].

$$\text{ABE}_i = (1-K) \cdot (1-p_m) \cdot T_s \cdot T_r \cdot C \qquad (5.17)$$

The simulation scenario used in [9] to derive the $f(m)$ function of Equation (5.18) included 4 nodes (2 of them hidden to each other). Simulations were carried out varying the packet size m.

$$f(m) = -5.65 \cdot 10^{-9} \cdot m^3 + 11.27 \cdot 10^{-6} \cdot m^2 - 5.58 \cdot 10^{-3} \cdot m + 2.19 \qquad (5.18)$$

This fixed scenario is more likely to be found in MANETs, although it seems to be quite different from vehicular scenarios where nodes follow streets in cities with buildings and respect traffic signs, the density of nodes and their speed may vary a lot throughout time, so many other aspects should also be considered. Because of this, we tried to improve the $f(m)$ function by making an analysis of data in our own simulations in VANET urban scenarios. We not only considered the packet size (m) as a variable, but also took into consideration other variables that are determinant in general realistic vehicular scenarios. Therefore, we also considered the node density (N) in the scenario and the average speed of the nodes (s). Our goal was to obtain a new function $f(m, N, s)$ to be included in the Equation (5.15) to estimate the ABE in Equation 5.17. This way the routing protocol will be able to take better forwarding decision to minimize the packet losses.

After the analysis (presented in Section 4.4.2) we obtain the final expression for $f(m, N, s)$, shown in Equation (5.19). Finally using $p_{m,N,s} = f(m, N, s) \cdot p_{hello}(m, N, s)$, see Equation (5.20).

$$f(m, N, s) = -7.475 \cdot 10^{-5} \cdot m - 8.983 \cdot 10^{-3} \cdot N - 1.428 \cdot 10^{-3} \cdot s + 1{,}984 \qquad (5.19)$$

$$p_{m,N,s} = f(m, N, s) \cdot p_{hello}(m, N, s) \qquad (5.20)$$

Finally, the value for the available bandwidth of each neighbour i is obtained using Equation (5.17) where p_m is now substituted by the new $p_{m,N,s}$, (ABE_i). Then, the algorithm assigns a value to the available bandwidth metric ($u_{4,i}$). The use of an exponential function helps us to emphasize good nodes compared to the others, which is closer to 1 when the bandwidth is very high, according to Equation (5.21)

$$u_{4,i} = e^{-\frac{1}{\mathrm{ABE}_i}} \tag{5.21}$$

5.2.6 Forwarding decision

MMMR takes forwarding decisions hop-by-hop based on geographic information. When a node wants to send a packet it has first to find the optimal next forwarding node from its list of neighbours.

When a sender node receives hello messages from its neighbours in transmission range, the node updates its neighbours list with all those nodes that sent their packets with enough power to be considered as a neighbour. After that, the node evaluates and assigns a total multimetric qualification to each neighbour. We assign the same weights (w_1, w_2, w_3, w_4) to each metric (u_1, u_2, u_3, u_4), respectively in the qualification of each neighbour. We leave for future work a further analysis to compute the set of weights. We obtain a global geometric metric with Equation (5.22). A global geometric score is used because it is less sensitive than arithmetic metric to extreme values of the metric components.

$$\begin{aligned}
\bar{u} &= u_1^{w_1} \cdot u_2^{w_2} \cdot u_3^{w_3} \cdot u_4^{w_4} \\
\bar{u} &= \prod_{i=1}^{4} u_i^{w_i} \\
\ln \bar{u} &= \sum_{i=1}^{4} w_i \cdot \ln u_i
\end{aligned} \tag{5.22}$$

To simplify the computation of the final value, the logarithmic of each metric is used as shown in Equation (5.23)

$$\begin{aligned}
\ln \bar{u} &= \sum_{i=1}^{4} w_i \cdot \ln u_i \\
&= w_1 \cdot \ln e^{-\left(\frac{d}{d_{ref}}\right)^{\alpha}} + w_2 \cdot \ln e^{-\left(\frac{\Delta d(t)}{d_{ref}}\right)^{\alpha}} + w_3 \cdot \ln e^{\frac{1}{\rho}} + w_4 \cdot \ln e^{-\frac{1}{\mathrm{ABE}}} \\
&= -w_1 \left(\frac{d}{d_{ref}}\right)^{\alpha} - w_2 \left(\frac{\Delta d(t)}{d_{ref}}\right)^{\alpha} - w_3 \frac{1}{\rho} - w_4 \frac{1}{\mathrm{ABE}} \\
-\ln \bar{u} &= w_1 \left(\frac{d}{d_{ref}}\right)^{\alpha} + w_2 \left(\frac{\alpha d^{\alpha-1} \parallel \vec{v} \parallel \cos\theta}{d_{ref}^{\alpha}}\right) + w_3 \frac{1}{\rho} + w_4 \frac{1}{\mathrm{ABE}}
\end{aligned} \tag{5.23}$$

We give a score to each node using the negative of the logarithm in the final calculation of the metric. Therefore, the best next forwarding node is the neighbour with the lowest multimetric value obtained applying the MMMR algorithm. As a starting point, we give the same degree of importance to all the metrics.

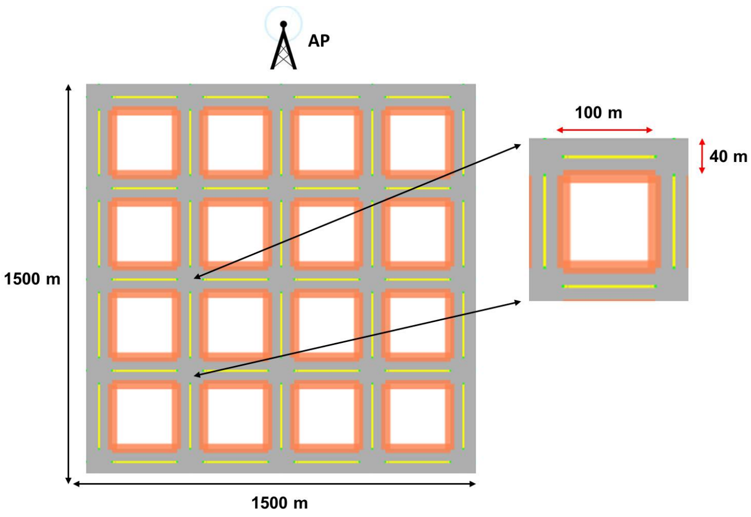


Figure 5.3: Length of the streets in the scenario.

5.3 Simulation results

Simulations were performed using the NCTUns 6.0 simulator [63]. We analysed the performance of our multimetric algorithm and we compared the performance of MMMR to AODV [44], GPSR [49], I-GPSR [53] and GBSR-B (Greedy Buffer Stateless Routing Building-aware) [59]. GBSR-B is our previous proposal to improve GPSR that includes a map-aware capability and a buffer mechanism instead of the perimeter mode, as it was explained in Chapter 3. GBSR-B only uses the distance as the metric to take forwarding decisions. We used a grid scenario to model a common urban scenario formed by streets and crossroads. Trying to simulate a realistic scenario we used Citymob [41] to generate the movements of vehicles that follow streets and respect the presence of other vehicles and traffic lights. The simulation area was 1500 m x 1500 m. We considered two densities of vehicles (60 and 120 vehicles) which were randomly positioned. Each street was 100 m long with intersections of 40 m (see Fig. 5.3) according to the area of the Eixample in Barcelona, Spain. The maximum average speed of the vehicles was 50 km/h. There was one fixed destination, an access point (AP, see Fig. 5.3), through which vehicles connect to the network to report traffic information. Half of the nodes sent 1000-bytes packets every 2 seconds to the unique destination during 1000 sec. There is an interferent traffic of 800 kbps. The transmission range of the nodes was 250 m and the sensing range was 300 m. All the figures are presented with confidence intervals (CI) of 99% obtained from five simulations per point. Table 5.3 summarizes the main simulation settings.

Table 5.3: Simulation settings.

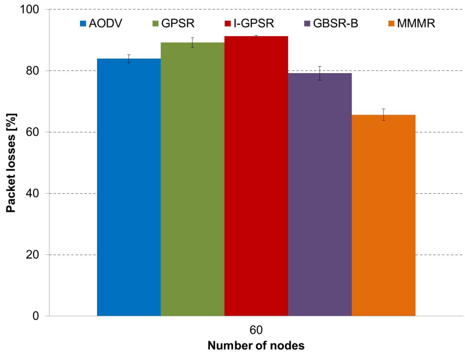
Parameter	Value
Simulation area	1500 m x 1500 m
Number of nodes	60 and 120 vehicles
Max. nodes speed	50 km/h
Transmission range	250 m
Sensing range	300 m
Mobility model	Manhattan
Mobility generator	Citymob
MAC specification	IEEE 802.11b
Bandwidth	11 Mbps
Simulation time	1000 sec.
Maximum packet size	1000 bytes
Routing protocol	AODV, GPSR, GBSR-B, I-GPSR, MMMR

5.3.1 A Multimetric, Map-aware Routing Protocol vs. other routing protocols

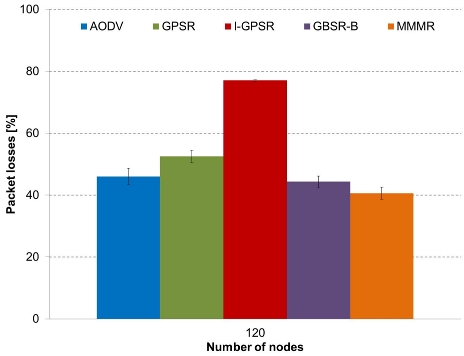
In this section we present the results of the evaluation of MMMR in two different scenarios: a sparse scenario with 60 nodes and a dense scenario with 120 nodes. Each one is analysed using different routing protocols to see the benefits that our routing protocol MMMR offers. All the nodes are randomly positioned. The well known routing protocols AODV and GPSR are evaluated as references. We implemented I-GPSR [53] because it is a vehicular routing protocol similar to our proposal. Also, we use our previous proposal called GBSR-B [59] that includes a buffer to temporary store packets instead of dropping them. Finally, we simulate our new proposal Multimetric Map-aware Routing protocol configured with a weight of 0.25 in each metric (see Equation (5.23)). We leave for a future work a further analysis to derive the optimum selection of weights based on machine learning techniques [79].

First, we can see in Fig. 5.4 the percentage of packet losses obtained by each one of the evaluated protocols. We can notice that MMMR obtains the best results in both scenarios. This is due to the optimal selection of the next forwarding node based on the four metrics that we propose to use. Moreover GBSR-B achieves a good result due to the use of the buffer that minimize packet losses improving at the same time the perimeter mode used in GPSR.

AODV is not an efficient routing protocol for VANETs because it establishes a full end-to-end path which is not suitable for VANETs due to high mobility of the nodes. When the link is established, however, it can successfully send a high number of packets, see Figs. 5.4(a) and 5.4(b). Meanwhile, GPSR uses periodically the perimeter mode (recovery path process) that is not very efficient and produces a high number of packet losses. Finally, we see that the highest number of packet losses is obtained by I-GPSR



(a) Sparse scenario.

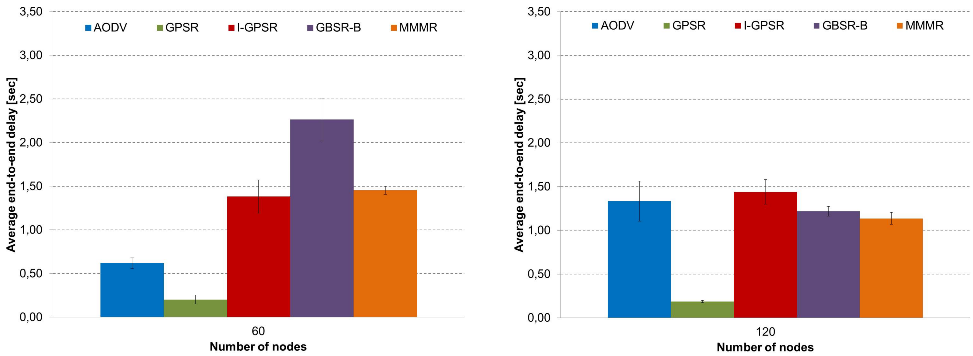


(b) Dense scenario.

Figure 5.4: Percentage of losses. (CI 99%).

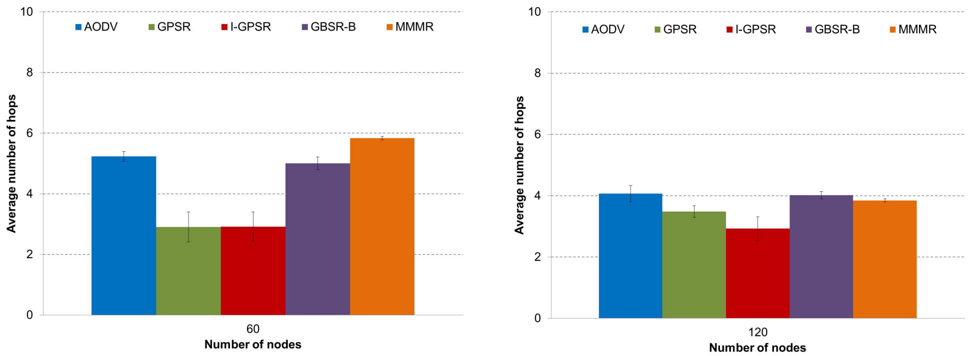
in both cases, sparse and dense scenarios. This behaviour of I-GPSR is mainly due to the selection of the next hop. The forwarding operation of I-GPSR is based on distance, speed, moving direction and density. I-GPSR prefers those vehicles that approach faster to destination. Since our urban scenario has a mobility model that includes stops (in crossroads), it can happen that sometimes the vehicles are completely static affecting the calculation of the score since I-GPSR thinks that such a stopped node is not a good forwarder node. We notice the same tendency in both scenarios in terms of packet losses, but with lower values in the dense scenario. The latter result has sense due to the presence of a higher number of neighbours which allows a better selection of the next forwarding node.

Fig. 5.5 shows the results of the average packet delay. The delay is calculated based on the packets that successfully arrived to destination. GPSR takes the forwarding decision considering only distance. Due to that, GPSR uses frequently the perimeter mode (recovery process), which increases the probability of packet losses. GPSR obtains the lower packet delay in both scenarios, see the second column in Figs. 5.5(a) and 5.5(b). That is because GPSR has a low number of received packets that are taken into account to compute the average delay. We can see the same behavior in both the sparse and the dense scenarios. GBSR-B obtains the highest delay due to the high amount of time that packets spend in the local buffer. This does not happen so frequent in the dense scenario due to the presence of a higher number of neighbours that allows a fast selection of an optimal next forwarding hop. The same happens with MMMR but with better results, since it also includes the building-aware capability and the improvement of the forwarding decision with the use of the four metric described in the previous section. In case of AODV (which sends RREQ/RREP messages to find a new full path and uses a buffer to minimize packet losses), in the sparse scenario (see Fig. 5.5(a)) packets that used the recovery process suffered a high loss probability and



(a) Sparse scenario. (b) Dense scenario.

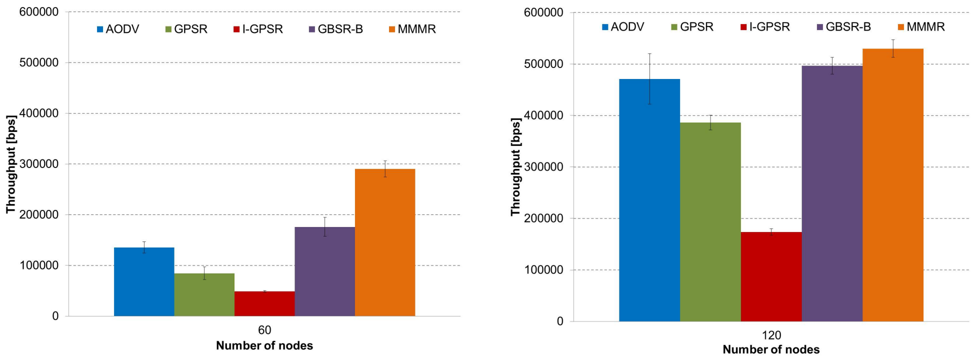
Figure 5.5: Average packet delay. (CI 99%).



(a) Sparse scenario. (b) Dense scenario.

Figure 5.6: Average number of hops. (CI 99%).

often did not achieve destination. Consequently, AODV obtains a low packet delay. In contrast, in the dense scenario (see Fig. 5.5(b)) packets that used the recovery process had a high probability to achieve destination (see Fig. 5.5(a)) due to the presence of a high number of neighbours that offers more options to forward the packets. However, packets suffered a high packet delay (Fig. 5.5(b)). Finally, we can see that I-GPSR obtains low delay in the sparse scenario due to the high number of packet losses that used a long path, so that they were not considered in the computation of the average delay. In the dense scenario I-GPSR obtains the highest delay compared to the other protocols, due to the process of the next forwarding selection that penalizes vehicles stopped momentarily in crossroads.



(a) Sparse scenario. (b) Dense scenario.

Figure 5.7: Throughput of received packets. (CI 99%).

In case of the average number of hops, depicted in Fig. 5.6, we notice that our MMMR presents the expected tendency of a high number of hops in a sparse scenario (Fig. 5.6(a)) and a lower number of hops in the dense scenario (Fig. 5.6(b)). The results in this case are very related to the next forwarding process of each protocol. We can see that GPSR (second column) and GBSR-B (fourth column) have the same tendency but GBSR-B delivers more packets successfully after many hops compared to GPSR. In AODV (first column) we can see that in the dense scenario there are paths with lower number of hops compared to the sparse scenario, but AODV spends more time in establishing the full path, obtaining therefore a high delay as we see in Fig. 5.5(b).

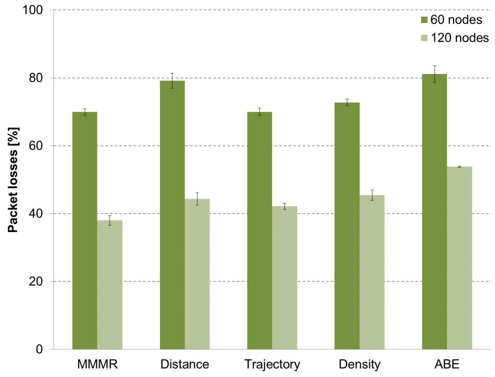
Finally, we see in Fig. 5.7 the throughput achieved using each protocol, Obviously, protocols with high packet losses obtain a low throughput. In contrast, low packet losses represent a high throughput.

The results confirm that the use of the combination of the four metrics to score candidates used in our Multimetric Map-aware Routing protocol (MMMR) to chose the next forwarding node, improves the selection of nodes in different environments compared to other routing protocols proposed for VANETs.

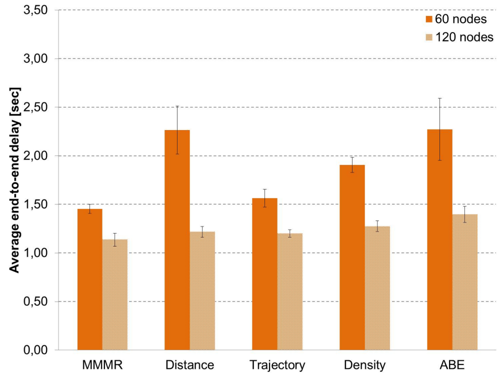
5.3.2 Performance evaluation of MMMR

In this section we present a performance evaluation of the Multimetric Map-aware Routing protocol that uses four metrics with the same weight each one and compared to the performance of the MMMR routing decision based only on one single metric. The evaluation was made in both scenarios (dense and sparse) and the results are depicted in Fig. 5.8.

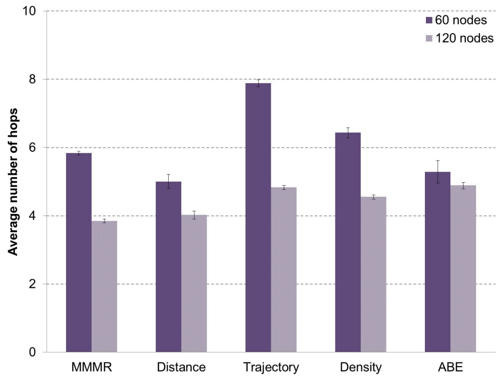
We can see that our proposal MMMR (first column) obtains the best results in terms of packet losses (see Fig. 5.8(a)), followed by the option of taking the forwarding decision



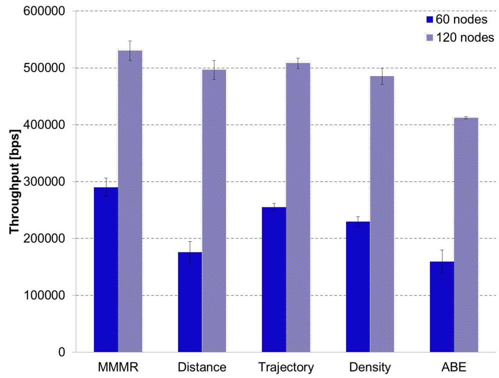
(a) Percentage of losses.



(b) Average packet delay.



(c) Average number of hops.

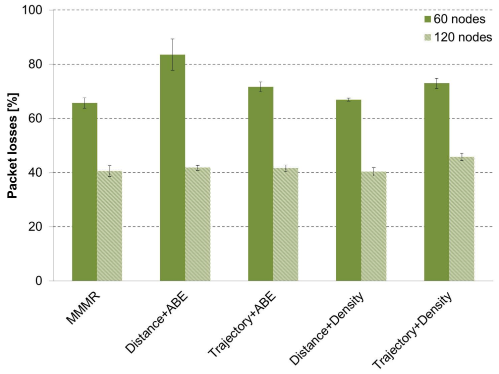


(d) Average throughput of received packets.

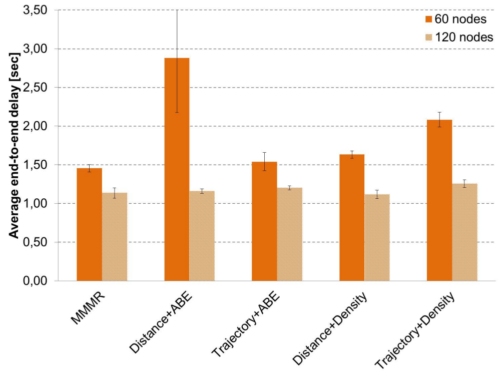
Figure 5.8: Performance of MMMR using single metrics in sparse (60 nodes) and dense (120 nodes) scenarios. (CI 99%).

based only on the metric "*Trajectory*" (w_1, w_2, w_3, w_4)=(0,1,0,0). The results obtained in terms of end-to-end delay (Fig. 5.8(b)) and the average number of hops (Fig. 5.8(c)) are best when the density of the scenario is high (120 nodes) because the probability to find a good neighbour is higher than in the case of sparse scenarios (60 nodes). In the sparse scenario the probability to use the buffer to store packets is high. Consequently, higher delays are obtained. The throughput achieved is related to the packet losses. Thus, in Fig. 5.8(d) we see that the dense scenario obtains higher throughput because lower losses were produced.

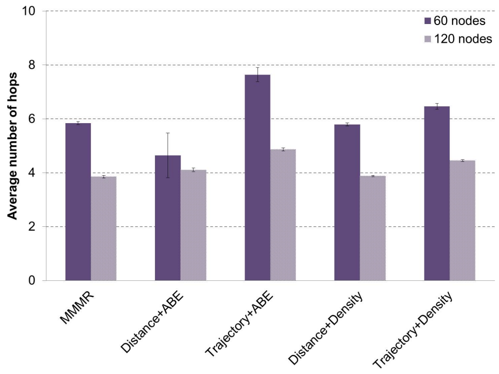
With these results we can conclude that our proposal, based on the use of four metrics to take forwarding decisions, is a good choice to decrease the packet losses in vehicular scenarios and to obtain a low delay in both dense and sparse scenarios.



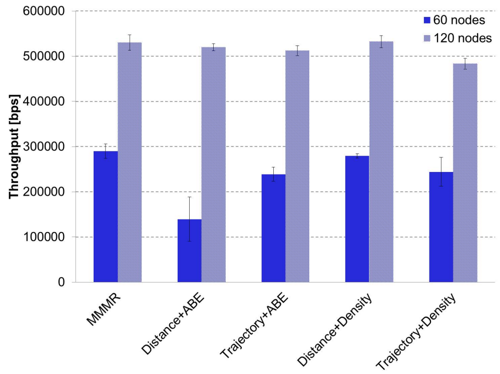
(a) Percentage of losses.



(b) Average packet delay.



(c) Average number of hops.



(d) Average throughput of received packets.

Figure 5.9: Performance of MMMR using combination of metrics in sparse (60 nodes) and dense (120 nodes) scenarios. (CI 99%).

In Fig. 5.9 we also present the performance evaluation of the MMMR protocol compared to the performance of the routing decision based on some combinations of metrics. Packet losses are slightly lower in the dense scenario when forwarding decisions are taken based on the combination metrics "*Distance+Density*" (w_1, w_2, w_3, w_4)=(0.5, 0, 0.5, 0). However, it is not the case in the sparse scenario where the best results are obtained for our MMMR (w_1, w_2, w_3, w_4)=(0.25, 0.25, 0.25, 0.25), see Fig. 5.9(a). These results prove that the density of the scenario is a very important parameter to obtain the final score to take the forwarding decision. The behaviour of packet delay and number of hops in the sparse scenario is the expected, i.e, a low number of hops produces a high delay, as it is the case of the "*Distance+ABE*" combination (w_1, w_2, w_3, w_4)=(0.5, 0, 0, 0.5). The reason is the use of the buffer, i.e., short paths in sparse scenarios mean

Table 5.4: Summary of combination metrics weights (sparse scenario).

Distance w_1	**Trajectory** w_2	**Density** w_3	**ABE** w_4	**% Losses**	**Average Delay sec**
0.25	**0.25**	**0.25**	**0.25**	**65.66**	**1.45**
1	0	0	0	79.17	2.26
0	1	0	0	70.02	1.56
0	0	1	0	72.79	1.91
0	0	0	1	81.14	2.27
0.5	0	0	0.5	83.50	2.88
0	0.5	0	0.5	71.62	1.54
0.5	0	0.5	0	66.90	1.63
0	0.5	0.5	0	72.98	2.08

Table 5.5: Summary of combination metrics weights (dense scenario).

Distance w_1	**Trajectory** w_2	**Density** w_3	**ABE** w_4	**% Losses**	**Average Delay sec**
0.25	0.25	0.25	0.25	40.58	1.14
1	0	0	0	44.36	1.22
0	1	0	0	42.13	1.20
0	0	1	0	45.47	1.27
0	0	0	1	53.81	1.40
0.5	0	0	0.5	41.75	1.16
0	0.5	0	0.5	41.56	1.20
0.5	**0**	**0.5**	**0**	**40.29**	**1.12**
0	0.5	0.5	0	45.75	1.26

that packets spent a while significant in the buffer. In the case of the dense scenario it shows a quite stable number of hops and lower delays because there is a higher number of neighbours and it is not necessary to use often the local buffer of the nodes to store packets temporarily till finding a good next forwarder, see Figs. 5.9(b) and 5.9(c).

We can conclude that the metric of the vehicle density is very important in both scenarios since it has a high impact in the results. Also, we can notice that it is possible to have good metric combinations that improve packet losses and delay, as it is the case of "*Distance+Density*" (w_1, w_2, w_3, w_4)=(0.5, 0, 0.5, 0) in the dense scenario.

In Tables 5.4 and 5.5 we summarize some combination of weights, the percentage of losses and the average delay obtained in each evaluation of combination of weights in the sparse and dense scenarios, see tables 5.4 and 5.5, respectively. We can see in Table 5.4 the best results are obtained with the MMMR combination of weights (w_1, w_2, w_3, w_4)=(0.25, 0.25, 0.25, 0.25). Obtaining the best results in terms of packet losses and average delay. In the case of the dense scenario, see Table 5.5, the best option is the combination "*Distance+Density*" (w_1, w_2, w_3, w_4)=(0.5, 0, 0.5, 0), where only distance and density are considered. The second best option is our proposal (w_1, w_2, w_3, w_4)=(0.25, 0.25, 0.25, 0.25) that includes a bandwidth guarantee by using the ABE algorithm.

5.4 Conclusions

In this chapter we have presented a new routing protocol for VANETs that includes four metrics to take hop-by-hop forwarding decisions. Also, the proposal is building aware avoiding those node in the transmission range but behind a build. This feature protects packets to the thrown. Besides,a local buffer is used to temporary store those when the routing protocol fails in finding a proper next forwarding node. We have analysed several metrics and developed an algorithm that includes four of them and a global score value used to select the best next forwarding node among all the neighbours in transmission range. Also, we present a performance evaluation taking into account the forwarding decision based on each single metric and several combinations of the four metrics to analyse the importance of each one depending on the scenario (dense or sparse).

As future work, we plan to analyse other methods to obtain a global metric value. Also, we want to optimize the computation of the weights of the metrics using machine learning techniques [79] so that the weights can vary throughout time making the algorithm self-configured to adapt the configuration to the changing network conditions that are inherent in VANETs.

Chapter 6

Anonymity in VANETs using a Crowds based algorithm

6.1 Introduction

The concept of intelligent transportation systems (ITS) emerged to communicate both infrastructure and vehicles, getting a communication platform to increase road safety. Also, there is an interest to provide infotainment services over VANETs which may require special guarantees such as Quality of Service (QoS) and privacy.

The huge potential of vehicle-to-vehicle connectivity is fundamentally due to the constant growth of automotive market and the increasing demand for car safety. Nevertheless, some issues related to routing, security, privacy and QoS should still be investigated. Providing QoS in VANETs is very complex due to the special features of these networks, such as high mobility nodes and large-scale node population. Privacy should also be preserved avoiding tracking a vehicle by non-trusted parties. Privacy could result in a multiple lawsuits after the network is deployed. Anonymity is a key concern in this kind of network. Guarantee the protection of the identity of a message sender is an important challenge and might be a mandatory feature for some VANET applications, i.e. reporting a traffic infraction in a city.

For this purpose, we introduce an anonymity and QoS-aware routing protocol that provides a mechanism for anonymous communications in VANETs. The main idea behind the anonymous routing protocol is to hide each user's communications by routing packets randomly within a group of similar users. Consequently, by using our anonymous routing protocol neither the receiver nor a corrupt group member or local eavesdropper that observes a message being sent by a particular user can never be sure whether that user is the actual sender, or is simply routing another user's message.

In this chapter, an anonymous routing protocol for vehicular networks in urban scenarios has been designed which not only improves the anonymity of communications, but also obtains good QoS performance. Our anonymity solution is based on the Crowds algorithm [3]. We use the Crowds algorithm over the well-known ad hoc routing protocols AODV [44] and GPSR [49], and also over our proposals GPSR-B and GBSR-B [59] presented in Chapter 3. In addition, our proposal is building-aware, so it is able to discard nodes behind walls which would lead to undesirable packet losses. Thus, our scheme is suitable for urban scenarios where buildings are obstacles for communications.

We evaluate QoS and privacy metrics in urban scenarios using our proposal. Such evaluation is done by implementing realistic vehicular scenarios using the mobility generator CityMob [41] and the network simulator NCTUns 6.0 [63] to carry out a performance evaluation analysing packet losses, end-to-end delay, average number of hops and an anonymity metric specially designed as well.

These design was developed and implemented in collaboration with Dr. Jordi Forné, Dr. David Rebollo-Monedero and Luis Urquiza [80]. The results are supported by two JCR publications: "On Collaborative Anonymous Communications in Lossy Networks" [81] and "A Collaborative Protocol for Anonymous Reporting in Vehicular Ad Hoc Networks" [82].

6.2 The need of anonymity in VANETs

Security is a major challenge. It is essential to make sure that life-critical information cannot be inserted or modified by an attacker. However, most security mechanism will result in significant overhead. This might seriously degrade the system capabilities in terms of latency and/or channel capacity. Privacy is another major challenge. To ensure accountability, messages need to be uniquely signed. However, the unique signatures will allow the signer to be tracked and eventually reveal its true identity.

In the vehicular network, it is highly desirable that users have their privacy in order to prevent their full identities from being disclosed. In the case of broadcast applications, the messages must not contain data that identifies the vehicle or that would allow a recipient to link messages, that is, to determine if multiple messages from dispersed locations and times came from the same vehicle. More precisely, the chance that an attacker can link messages must drop off rapidly with the distance and time between the transmissions of the two messages. This requirement must be satisfied consistently with also requiring that messages are authenticated. In other words, preventing an attacker with a radio unit from inserting messages into the system that did not actually originate from a particular vehicle.

In the case of transactional applications, the vehicle may choose to reveal its identity, or at least reveal linkable data, to a trusted respondent. However, it will not wish to reveal this data to any other entity.

Anonymity is difficult to provide in vehicular networks, because much of the information in the messages is identifying. A vehicle could be tracked by its unique IP address, MAC address, digital signature and certificate, and account or billing information for transactional applications. In general, in the vehicular network traffic it is essential to ensure network robustness through security protocols that work despite misbehaving participants. The future vehicular networks must assure anonymity. With anonymity the full identity of a vehicle sending each packet/data should be kept private.

6.3 General operation of the Crowds algorithm

The main idea behind the Crowds algorithm [3] is based on the idea of "blending into a Crowd", i.e, hiding one's actions within the actions of many others. With this basis, in routing protocols the finality is not to be able to identify the initiator of a sent message, since the initiator is indistinguishable from another member in the network that simply forwards the messages from another. Using Crowds, a corrupt group member or local eavesdropper that observes a message being sent by a particular user can never be sure whether the user is the actual sender or if that user is simply forwarding another user's message. Crowds works by making each node seem equally likely to be the initiator of the message.

Fig. 6.1 shows an example of the Crowds operation [3], where there are a number of users (in circles) who want to access a given number of web servers (in squares) with certain anonymity. The sender node has to randomly choose another node (with uniform probability) from all nodes in the network and forward the message to that node. Upon receiving the message the current node flips a biased coin (with probability $p > \frac{1}{2}$) to determine whether or not to forward the request to another node. The result can be forward the packet, so the sender node selects a random next forwarding node and send the packet, otherwise the sender node sends the packet to the final destination directly.

In Fig. 6.1 the possible paths are $1 \rightarrow 5 \rightarrow$ server; $2 \rightarrow 6 \rightarrow 2 \rightarrow$ server; $3 \rightarrow 1 \rightarrow 6 \rightarrow$ server; $4 \rightarrow 4 \rightarrow$ server; $5 \rightarrow 4 \rightarrow 6 \rightarrow$ server; and $6 \rightarrow 3 \rightarrow$ server. Subsequent requests initiated at the same source follow the same path (except perhaps going to a different end server), and server's replies traverse the same path as the requests, following the reverse way. Each node that forwards a packet to another node records the predecessor path identifier and replaces it by a new path identifier that occupies multiple positions on a path to act independently in each position. In this way, a virtual tunnel is built, which is used for the communication between sender and receiver. As each node only stores information about its predecessor, it is impossible for an intermediate node to be aware of neither the whole path nor the sender identity. In our analysis of the Crowds algorithm we only use unidirectional communication.

We consider the presence of collaborator Crowd's members that are single malicious attackers. The goal of the collaborators is to determine the member that initiated the path, this means to detect which node is the source node.

In order to yield probable innocence for the path initiator, the probability of forwarding (p) must be greater than $\frac{1}{2}$ in the network. That means, due to the required first random hop in the original Crowds with p lower than $\frac{1}{2}$ increase the probability

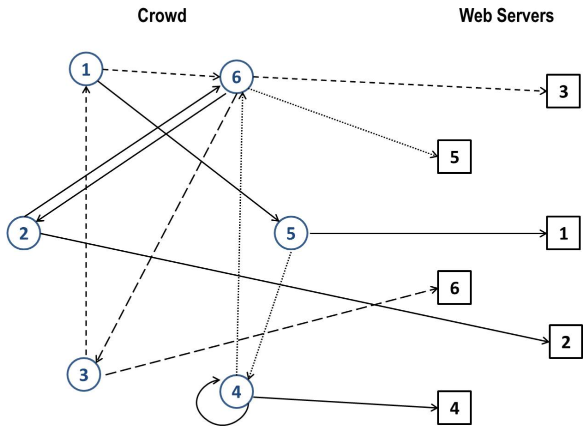


Figure 6.1: Crowds operation [3].

that a c identifies the real source of the packet. Let c denote the number of collaborators in the Crowds algorithm, and let n denote the total number of Crowd's members when the path is established.

$$Identity\ of\ the\ path\ initiator = \frac{n - p_f(n - c - 1)}{n} \tag{6.1}$$

The Equation (6.1) could be seen as the difference of 1 and the probability that collaborators do not determine the identity of the path initiator; the mentioned probability is directly proportional with the forwarding probability p and the number of collaborators c and in the other side it is inversely proportional with the number of Crowd's members n.

The author of Crowds establish a relationship between the number of member n and number of collaborators c for getting a determinate probability of collaborators knows the identity of a message's sender. That is, if the number of collaborator increases, the probability to identify the originator of a packet increases too.

The original procedure of Crowds establishes that the initiator's path must select randomly the first hop from the n members including itself, given no chance that the destination could be reached in one hop, see Equation (6.2). This approach produces that for the end server it is equally likely to receive the initiator's requests from any Crowd's member.

$$PathLenght = \frac{p}{1 - p} + 2 \tag{6.2}$$

The Crowds variant used in this thesis eliminate the required first random hop, given the opportunity that the path initiator can send the packets directly to the destination. This analysis try to decrease the probability of losses because a higher number of hops will produce more losses in VANET urban scenarios. This modification tries to increase the opportunity to packets coming from multihop paths to reach the destination.

The Crowds variant as was said, needs less hops than the original Crowds, but it gives a higher probability to the end server, Access Point (AP), to guess the source node. Therefore, the medium path length expected depends only on p (probability of forwarding) as it can be seen in Equation (6.3) that is a variation of Equation (6.2) without the first required random hop.

$$PathLenght = \frac{1}{1-p} \tag{6.3}$$

The behaviour of the Crowds mechanism used in this thesis is identically to the original Crowds in the collaboration attack. That is, the probability of c collaborators know the identity of the sender node using the Crowds algorithm depicted in Equation 6.1.

6.4 Implementation of the CROWD algorithm in VANETs

In this chapter we compare the performance of Crowds mechanism over two well-known ad hoc routing protocols: AODV [44] and GPSR [49], and also over our own proposals GPSR-B and GBSR-B, which where previously explained in Chapter 3.

6.4.1 Adaptation of Crowds in vehicular scenarios

The motivating scenario of this chapter is a vehicular ad hoc network in urban environments. In this subsection, our purpose is to elaborate on the specific type of VANETs upon which our anonymous protocol builds.

As we already know, this kind of networks allows users to both exchange messages among them and submit messages directly to the network infrastructure. These two forms of communications are referred to as vehicle-to-vehicle communication and vehicle-to-infrastructure communication, respectively.

In addition, such communications enable users to report common traffic offenses such as speeding, red light violation or tailgating, as well as traffic incidents such as accidents and traffic jams. Further, it is expected that these networks will support entertainment applications in the near future. All these services are foreseen to be provided in the promising smart cities in the next years [83].

In this chapter, we evaluate the performance of the implementation of Crowds algorithm over routing protocols in VANETs considering packet losses and a number of other causes explored in Section 6.5.

Finally, we assume that there exists a single, fixed access point (AP) to which all users within a bounded area, e.g., neighbourhood, send their reporting messages. We consider this last assumption describes a fairly realistic scenario, owing to the costly

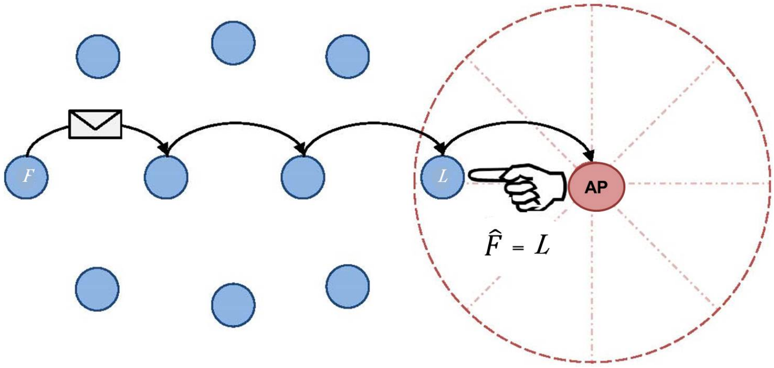


Figure 6.2: Adversarial model (AP playing the role of the privacy attacker). F= first sender, L=last sender, AP= Access Point.

deployment of these networks. In this specific scenario, we assume that the access point is not within the communication range of every user, what leads these users to use a multihop routing protocol to deliver their messages. Specifically, when a user witnesses a traffic violation, they immediately submit a message to the next user in the route determined by the routing protocol. The message includes identifying information about the offender, the GPS coordinates where the offense was committed and the time when it was observed. When this next user receives the message, they forward it to another user and so on until the message reaches its destination. When this finally happens, the access point adds the message to a traffic infractions list, which users can download afterwards to verify whether their reports have been received successfully.

6.4.2 Adversarial Model

In our scenario, it is the access point who plays the role of the privacy attacker. The users involved in the multihop routing protocol, however, are assumed to be partially trusted. This is in the sense that, while they are agreed to route messages, they may attempt to compromise the privacy of users reporting traffic violations. As we discussed in Section 6.4.1, in our application scenario users reveal their position, though *not* their identity, when submitting reports to the access point.

In this thesis we assume that, upon reception of a message, the attacker's objective is to ascertain the *identity* of its originator. Note that, under this adversarial model, the re-identification of users is not the only privacy threat-based on the locations of the infractions reported by such users. The attacker could track them and ultimately extract sensitive information such as the places that a user usually visits, e.g., school, shops, home.

In the end, our last assumption has to do with the attacker's strategy to determine the originator of a message. More precisely, we assume that the attacker strives to guess the identity of the *first* sender (originator) of a given message, knowing *only* the user who *last* forwarded it. This could be interpreted as an adversary with a local view of the network, possibly due to their limited coverage range.

Mathematically, we model the first sender and the last sender by the random variables F and L, respectively. Since the only information available to the attacker is L, we consider that the attacker's estimator of F is directly the following:

$$\hat{F} = L \tag{6.4}$$

That is, the attacker chooses the last sender as the originator of the message. Fig. 6.2 illustrates the assumptions of our adversarial model.

6.4.3 Description of the anonymity-aware routing protocol

In this subsection we present the main contribution of this chapter, an anonymous routing protocol for the reporting of traffic offenses in vehicular ad hoc networks. The primary purpose of this protocol, as its name indicates, is to enable users of these networks to report traffic infractions in a manner that neither the access point nor the users participating in the protocol cannot compromise the anonymity of reporting users.

Our approach builds on top of multihop routing protocols such as AODV, GPSR, GPSR-B and GBSR-B. Since our approach is greatly inspired by the popular anonymous-communication system Crowds [3], next we underline the main differences with respect to our proposal.

- Firstly, Crowds is a unihop protocol inasmuch as every member can forward a request directly to a Web site, or in general, to an untrusted receiver. Our approach, which is specifically designed for a *mobile* scenario, does not contemplate this possibility, though. Basically, this is due to the limited communication range of vehicles in our scenario. As a consequence of this limitation, a user participating in the protocol cannot forward a message to any member of the system. Instead, the user has to content themselves with submitting it to one of their neighbouring members, that is, those within their coverage range.

- Secondly, we do *not* introduce a mandatory initial forwarding step as Crowds does. The reason is that such initial step imposes a price on the average delay.

- Lastly, in our protocol users forwarding messages do not need to store information about their predecessors. As we will see later, users will confirm the reception of their messages by downloading a list of encrypted messages, released by the access point.

Having examined the differences between Crowds and our approach, next we set forth the details of our anonymous routing protocol. For this purpose let us consider the scenario described in Section 6.4.1 and a multihop routing protocol used by every user in that scenario. Under these premises, suppose that a user witnesses a traffic offense and decides to report it to the access point.

When a user wants to send a message, the user finds out which users are within its coverage range. Among these neighbouring users, the routing protocol chooses a candidate to forward the message. We would like to note that the choice of this candidate will vary depending on the specific routing protocol assumed. With this information, the user decides either to send the message to that candidate, or to submit it to another neighbouring user chosen uniformly at random.

Similarly to the original Crowds, the user opts for the former strategy with probability p, and adopts the latter with probability $1-p$.

Upon receipt of the message by this neighbouring user, they repeat the same forwarding technique. That is, the user chooses probabilistically whether to submit the message to the neighbouring user recommended by the routing protocol, or to send it to another randomly chosen user within their coverage range. This process goes on until the message reaches its destination. When this is the case, the access point cannot ascertain whether the user who last forwarded the message was actually its originator or was merely forwarding it on behalf of another user. In the end, we would like to emphasize the fact that our approach strongly depends on two factors, first, the forwarding probability p; and secondly, the concrete multihop routing protocol integrated into our protocol, which decides the next forwarding user in the route towards the access point.

The remainder of this chapter is entirely devoted to the evaluation of the performance of our proposal, both in terms of QoS and anonymity, under the consideration of the underlying routing protocols AODV, GPSR, GPSR-B and GBSR-B and using different values of p.

6.4.4 Using Crowds over AODV

This section describes the implementation of the Crowds algorithm over AODV in the NCTUns 6.0 simulator, done with the collaboration of Luis Urquiza [80]. The Crowds algorithm was developed to support a two-way communication, therefore reply (acknowledgment or feedback) is required. However, in this thesis our implementation of Crowds over AODV describes the procedure followed only for one way communication. Due to the was designed considering services that do not required feedback.

The Algorithm 5 shows the decisions included in AODV, where p is the probability of the Crowds forwarding. First, it is necessary to generate a random value. If the random value generated is higher than p the transmission has to be done with Crowds (lines 1 to 7). When the Crowds mechanism is chosen to send a packet, the neighbour list is checked to verify if it is empty. If the node does not have neighbours, the packet will be dropped; otherwise a random neighbour from the list of neighbours will be chosen as the next forwarding node.

In case that the value of p is lower than the random value the transmission has to be done with classical AODV (lines 9 and 10), searching a established path to destination

Algorithm 5 . Crowds algorithm over AODV.

```
Require: Packet arrives
Require: Generate a random value
Require: p = x
 1: if randomValue > p then
 2:    if (NeighboursList != 0) then
 3:       NextHop = RandomNeighbour
 4:       SendPackets
 5:    else
 6:       DropPackets
 7:    end if
 8: else
 9:    if (AODVPath = 0) then
10:       SendPackets
11:    else
12:       Store packets in buffer
13:       SendRREQ
14:       if (RREP) then
15:          SendPackets
16:       else
17:          DropPackets
18:       end if
19:    end if
20: end if
```

and sending the packets. It could happen that an intermediate node which receives a packet using the Crowds mechanism has to forward the packet using the normal AODV operation. If this node has no route, it would throw away the packet as a consequence. To avoid this situation, we modified AODV to store the packet in a temporary buffer and in the meantime be able to send a RREQ when the route in an intermediate node is marked as not existing (lines 12 to 17).

6.4.5 Using Crowds over GPSR

This section describes the functionality of the Crowds mechanism over GPSR in a one-way communication. The procedure followed to implement Crowds over GPSR is basically the same used in AODV, with the main difference that the selection of the next forwarding node follows the hop-by-hop mechanism of GPSR, see Algorithm 6. Basically, a random value is generated, if the random value is higher than p (crowd probability) the crowds mechanism is used (lines 2 to 7). The neighbour list is verified. If it is empty the packet is dropped, otherwise a neighbour is selected randomly as next hop. In case p is higher than the random value generated, the protocol GPSR works

Algorithm 6 . Crowds algorithm over GPSR.

```
Require: Packet arrives
Require: p = x
Require: Generate a random value
if randomValue > p then
  if (NeighboursList != 0) then
    NextHop = RandomNeighbour
    SendPackets
  else
    DropPackets
  end if
else
  if (NeighboursList != 0) then
    if NeighbourDistance < CurrentDistance then
      NextHop=ClosestNeighbour
    else
      PerimeterMode
    end if
    SendPacket
  else
    DropPackets
  end if
end if
```

normally, selecting the closest neighbour to destination as next forwarding hop.

Due to hop-by-hop routing strategy used by GPSR, it was simple to add the Crowds strategy. As with Crowds over AODV implementation, Crowds over GPSR implementation does not have any mechanism to avoid packet losses. That means that when there are no neighbours to forward packets in the neighbour list the packet is dropped.

As it was described in Section 3 we made some improvements in GPSR. In this performance evaluation we include Crowds mechanism in our two proposals GPSR-B (GPSR with buffer) and GBSR-B (Greedy Buffer Stateless Routing Building-aware) in order to evaluate the performance of the Crowds algorithm in all cases. Algorithm 7 presents the conditions to be satisfied when Crowds works over GPSR-B. GBSR-B works in the same conditions, but the optimal next hop is selected as Algorithm 3 shows in Section 3.3.

Algorithm 7 . Crowds algorithm over GPSR-B.

Require: Packet arrives
Require: p = x
Require: Generate a random value

```
if randomValue > p then
   if (NeighboursList != 0) then
      NextHop = RandomNeighbour
      SendPackets
   else
      DropPackets
   end if
else
   if (NeighboursList != 0) then
      if Neighbour < TransmissionRange then
         if Neighbour == LOS then
            if NeighbourDistance < CurrentDistance then
               NextHop=ClosestNeighbour
               SendPacket
            else
               SendPacketToBuffer
            end if
         else
            SendPacketToBuffer
         end if
      else
         SendPacketToBuffer
      end if
   else
      SendPacketToBuffer
      SearchNewNextForwarding
      if NewNextForwarding then
         SendPacketfromBuffer
      else
         DropPacketsfromBuffer
      end if
   end if
end if
```

6.5 Evaluation of Crowds over VANET scenarios

In this section we present the simulation environment represented in Figs. 6.3 and 6.4. In each scenario we evaluated the performance of each routing protocol (AODV, GPSR, GPSR-B, GBSR-B) with and without using the Crowds algorithm. We used several values of p (5%, 25%, 50%, 75% and 100%), which is the probability that the protocol operates normally whereas 1-p is the probability of selecting randomly the next forwarding hop according to our modified Crowds algorithm described in section 6.4. We included the Crowds algorithm in all the routing protocols evaluated and we compared their performance.

Simulations were done using the NCTUns 6.0 simulator [63], where we implemented GPSR, GPSR-B and GPSR-BB. AODV was already implemented. We included the Crowds function in all the protocols evaluated. The data rate used was 11 Mbit/s. The propagation model employed in our simulations was the Two Ray Ground, which consists of a direct signal and an indirect signal produced by ground reflexion. IEEE 802.11p is not implemented yet in NCTUns. Thus, we used IEEE 802.11b since both have the same MAC operation. The only difference is that IEEE 802.11p improves the physical layer for high speeds, so we could expect even better results with IEEE 802.11p.

Vehicles move according to the mobility generator CityMob [41]. This mobility generator allows us to create realistic urban mobility scenarios where vehicles follow streets and respect traffic signals. We selected the Manhattan mobility model. The urban scenarios have 60 nodes randomly positioned in the streets. There are eight 100 m x 100 m streets and each intersection measures 40 m, according to the city of Barcelona, Spain. There are traffic lights at each intersection. At intersections, vehicles randomly can turn right, left or continue in the same direction.

Each node transmits constant bit rate (CBR) flows at a rate of 1 packet every 2 sec. Each flow is composed of 1000-byte packets. Only one destination is placed in the scenario, which is the access point (AP) represented in Figs. 6.3 and 6.4. We carried out several simulations for each scenario and confidence intervals of 99% are shown in the figures obtained from 5 repetitions per point. Table 6.1 shows the most representative simulation parameters. The main differences of the tested scenarios are as follow:

- A unihop scenario where all vehicles are in the same transmission range, T_x=1000 m, see Fig. 6.3.
- A scenario where vehicles have a transmission range of T_x=250 m, i.e. not all the vehicles are in the same coverage area and therefore the AP is not reachable directly from every node, so there may be multihop paths, see Fig. 6.4.
- A more realistic urban scenario that includes walls that block the transmission signal. Vehicles have a transmission range of T_x=250 m. The scenario is the same as the one shown in Fig. 6.4 but including total block of the signal in the presence of buildings.

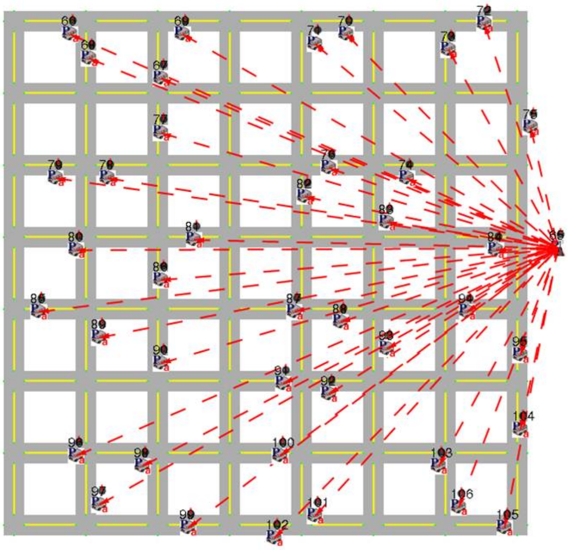


Figure 6.3: Unihop scenario: all the vehicles are in the same transmission range.

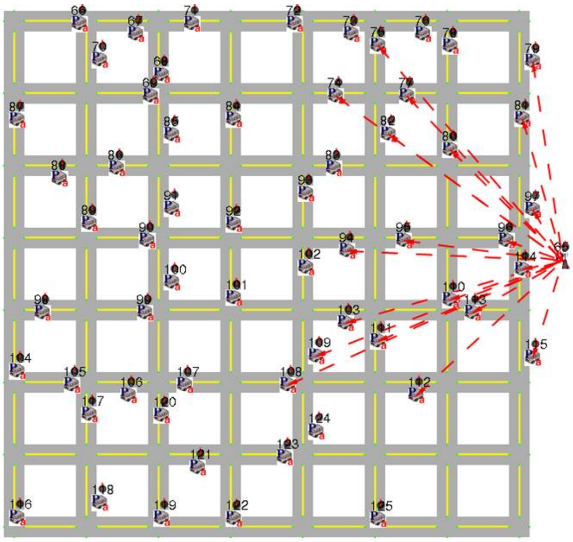


Figure 6.4: Multihop scenario: not all the vehicles are in the same transmission range.

Table 6.1: Simulation settings in Crowds evaluation.

Parameter	**Value**
Medium capacity	11 Mbps
Packet size	1000 bytes
Traffic source	CBR
Transmission range (T_x)	250 m and 1000 m
Carrier sensing range (S_x)	300 m and 1200 m
Simulation time	1000 sec
MAC specification	IEEE 802.11b
Area	1020 m x 1020 m
Maximum speed	50 km/h (14 m/sec.)
Number of nodes	60
Propagation channel model	Two Ray Ground
Radio propagation	Rician
Mobility generator	CityMob [41]
Mobility model	Manhattan
Routing protocol	AODV, GPSR, GPSR-B, GBSR-B
Crowd probability (p)	5%, 25%, 50%, 75% and 100%

6.5.1 Evaluation of results in a unihop scenario

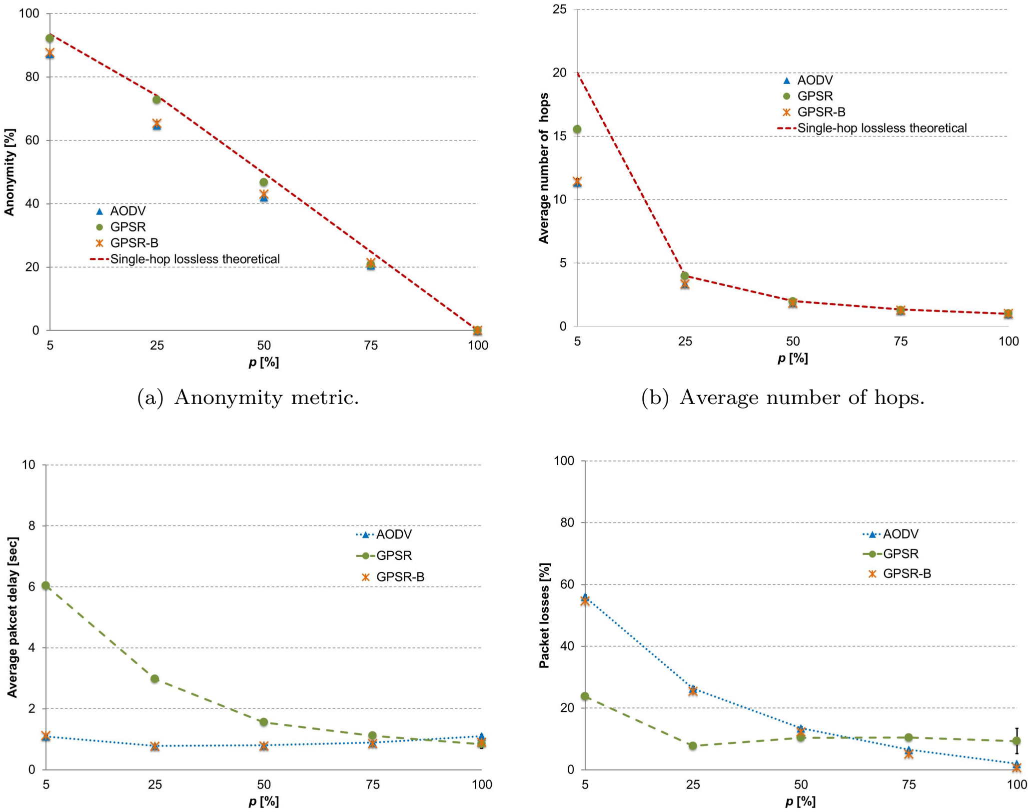
We first focus on a unihop scenario. All nodes send information to the unique AP destination. In this case all nodes are in the same coverage range (see Fig. 6.3), which is an ideal scenario to evaluate the theoretical analysis of the routing protocols using the Crowds algorithm.

The results in this scenario are represented in Fig. 6.5. The metric of anonymity measures the probability that the AP guesses who was the source of the received packet by applying the criterion that the source was the node who delivered the packet. According to Fig. 6.5(a), GPSR shows a slightly better performance in anonymity than GPSR-B or AODV, showing the closest results to the *single-hop lossless theoretical analysis* [81] that represents Equation (6.5).

$$P\{F = L\} = \frac{1 + (n-2)\cdot p}{n-p} \tag{6.5}$$

Where we see that the probability that the last forwarding node is equal to the source of the packet depends of the number of nodes in the scenario (n) and the probability of use Crowd (p) in the forwarding decisions.

The results in all cases are lower that the theoretical because in this scenario there are packet losses, which are not taken into account in the model. That is, packets which used less number of hops to reach destination successfully have a higher influence in the calculation of the average number of hops compared to those packets that used



(a) Anonymity metric.

(b) Average number of hops.

(c) Average packet delay.

(d) Percentage of packet losses.

Figure 6.5: Unihop scenario. AODV, GPSR and GPSR-B metrics as a function of the Crowd probability (p) (CI 99%).

larger paths, since they suffered a loss with higher probability (i.e. those packets did not arrived to destination and thus did not contribute in the average).

The three protocols show the same tendency of higher anonymity for lower p values, i.e., when the protocols operate with the Crowds capability. This has sense, because for lower p values, next forwarding nodes are more often chosen randomly, so higher is the anonymity. In such cases, the AP will highly doubt about if the received packet was delivered by the source node or just by a forwarding node. When p=100%, i.e., the packet is directly delivered to the AP, there is no anonymity in a unihop scenario, since all nodes are neighbours and thus the AP knows positively who was the source node of the received packet.

Fig. 6.5(b) shows the average number of hops of the paths from source to destination.

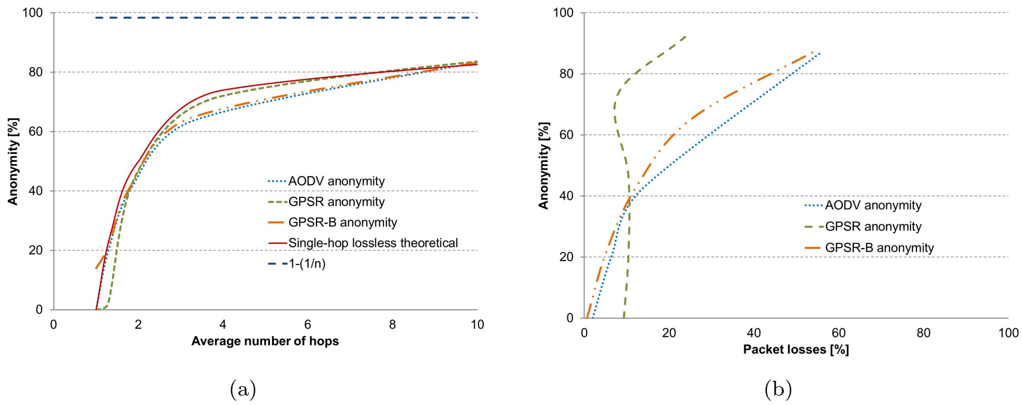


Figure 6.6: Percentage of anonymity as function of a) average number of hops and b) percentage of losses in the unihop scenario.

We can see that AODV and GPSR-B present lower results than expected when p=5%. This is due to the operation of GPSR-B and AODV, which also have a buffer to store packets to avoid dropping them. Notice that using AODV, after storing a packet in the buffer an alternative end-to-end path has to be found, so it is possible that packets that used paths with higher number of hops do not achieve destination and thus they do not contribute to compute the average number of hops. That is not the case of GPSR which has no such buffer, so that the average number of hops fits well with the single-hop lossless theoretical values.

For GPSR, which does not use any buffer, the average delay shows the same tendency that the average number of hops, see Fig. 6.5(c). However, this is not the case for AODV nor GPSR-B. The reason is that both protocols use a buffer to store packets instead of dropping them when there is no next forwarding node. This produces an additional delay time in that buffer, which may trigger a timeout in the packet which would discard it.

In Fig. 6.5(d) the percentage of losses is shown. We can see that AODV and GPSR-B have the same behaviour of higher losses for lower p. This is because these protocols loss more packets when they operate with Crowds. Conversely, they show a better behaviour than GPSR when p is 100%, i.e., the normal protocol without anonymity, thanks to the buffer to store packets instead os dropping them. Notice that from Figs. 6.5(c) and 6.5(d) we can conclude that for normal operation of the protocols (i.e. $p \rightarrow 100$), GPSR has lower delay and higher losses than AODV. Lower delay is due to GPSR does not use buffer to store packets if a next forwarding node is not found. Besides, the higher losses in GPSR is due to the fact that the perimeter mode produces loops trying to avoid the area without neighbours.

Conversely, for Crowds operation (i.e. $p \rightarrow 0$) GPSR shows higher delay and lower losses than AODV. The reason is that including the Crowds algorithm in AODV, packets successfully delivered used shorter paths compared to GPSR, which makes that AODV presents lower delay than GPSR. Also, using Crowds in AODV packets that needed longer paths were dropped (due to link breakages) or discarded (due to timeout) more aggressively than with GPSR, which produces higher losses using AODV than GPSR.

Fig. 6.6(a) shows the results of the anonymity as a function of the number of hops. We can see that GPSR is the closest to the single-hop lossless theoretical results $(1-\frac{1}{n})$. The reason is that using GPSR for high p values the number of hops in the paths was high in all cases, whereas for the other protocols was not so high. In the other case Fig. 6.6(b) shows the results of the anonymity as a function of the percentage of losses. We can see that losses in AODV and GPSR-B increase when anonymity is higher. GPSR does not increases more than 23% in losses even when anonymity increases to 85%.

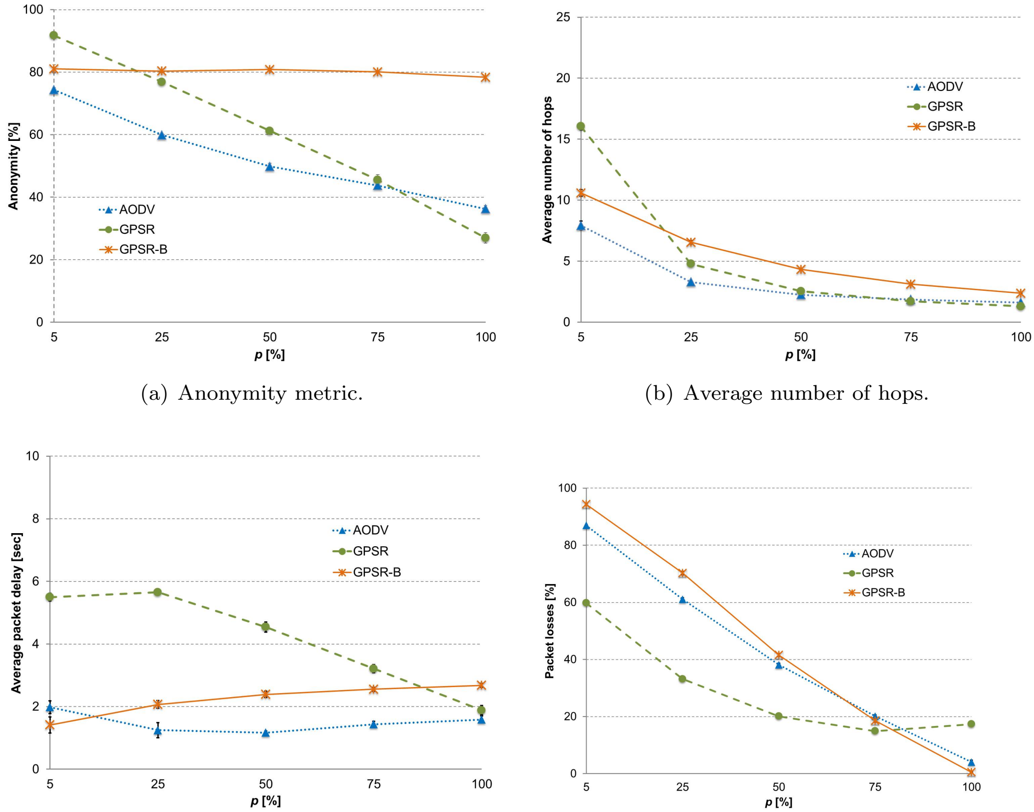
6.5.2 Evaluation of results in multihop scenarios

Our second scenario contemplates an urban environment without buildings. This special case has the advantage that radio signals cannot be blocked by any wall. In the next Section 6.5.3 we include buildings in the scenario so that comparing results we will be able to see the effect of taking into account the buildings in our proposal and also the importance of including them in realistic simulations.

It is important to highlight that the end-to-end behaviour of AODV causes paths to break. As a result, with low values of p the protocol needs to resort more often to recovery processes, which increase the use of signalling messages (RREQ and RREP packets) to find a new full path. This ultimately increases losses during the recovery phase. Notice that this behaviour is not present in GPSR since its path construction is hop-by-hop.

Our experimental results show that GPSR holds the expected behaviour of a routing protocol that implements Crowds without any mechanism to avoid or prevent packet losses. That is, with a higher probability to send the packet directly (p=100%) there are less packet losses, less delay, less average number of hops and less anonymity level. GPSR exhibits the highest anonymity level when p is lower than 25% (see Fig. 6.7(a)). This is because using GPSR in a random way (i.e low p) more packets with a higher number of hops were able to achieve destination, specially compared to AODV. The reason is the hop-by-hop routing scheme used by GPSR, whereas AODV needs end-to-end paths. Packets that arrived from paths with more than one hop have a high anonymity, since in paths with more than one hop the AP will fail more often in guessing the actual sender.

GPSR-B presents the highest anonymity level because it uses a buffer which avoids losses of packets that arrived from paths with more than one hop. So the AP may fail more in finding out who the actual source of the packet was, producing a constant anonymity whatever p is. Notice that the AP only guesses the real source of the packets (i.e. anonymity=0) received from one-hop paths. This is because the AP chooses the



(a) Anonymity metric.

(b) Average number of hops.

(c) Average packet delay.

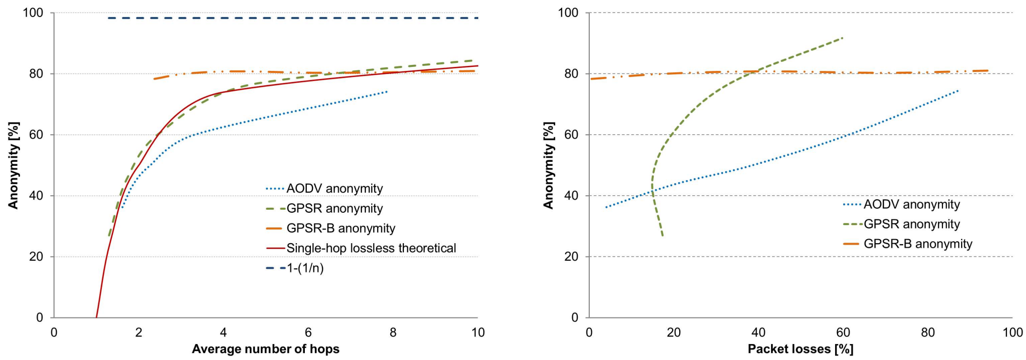
(d) Percentage of packet losses.

Figure 6.7: Multihop scenario without buildings. AODV, GPSR and GPSR-B metrics as a function of the Crowd probability (p) (CI 99%).

last sender as the source of the packet (see Equation (6.5)).

The three protocols show the same tendency with p in terms of the average number of hops (see Fig. 6.7(b)). As p grows, paths have a lower number of hops and consequently the percentage of packet losses will decrease (see Fig. 6.7(d)). AODV presents a lower number of hops than the other two protocols, specially for low values of p (see Fig. 6.7(b)). This is because after several hops, the end-to-end path may be interrupted. When this happens, the routing protocol must find a new path, probably shorter. However, AODV loses a higher number of packets during the recovery time of the path. Hence, most of the packets that get the AP arrived from short paths.

Figure 6.7(c) shows the average packet delay. GPSR presents the highest delay because GPSR delivers the highest number of packets which arrived from paths whose



(a) (b)

Figure 6.8: Percentage of anonymity as function of a) average number of hops and b) percentage of losses in the multihop without buildings scenario.

average number of hops was high, increasing the average delay computation compared to the other protocols. AODV presents the lowest delay almost in all the points, except when p=5%, where the high random selection of the next hop causes that paths break often and AODV needs more recovery processes (higher number of RREQ and RREP packets to find a new path), which increases the delay. AODV shows less delay than GPSR because the computation of the average delay was made mainly from packets that achieved destination with a lower number of hops compared to GPSR. Also, AODV shows less delay than GPSR-B because AODV makes a lower use of the buffer, so packets do not spend so much time in the buffer.

In terms of packet losses, GPSR-B and AODV present high losses in all the cases (see Fig. 6.7(d)). The three protocols produce higher losses for low p values, since packets wander around using longer paths so the chance of losing a packet is higher. GPSR-B losses more packets than AODV since GPSR-B uses a higher number of hops (see Fig. 6.7(b)) and expends more time selecting the next forwarding node (using a smarter algorithm) and thus GPSR-B discards more packets (whose timeout expired) from the buffer. AODV, on the other hand, provides an anonymity protection lower than GPSR basically due to the high packet loss ratio of the former. This is mainly caused by the constant path breakages and the use of a buffer in the path recovery process. More precisely, nodes try to send the buffered packets when a RREP is received, resulting in a higher probability of collisions because this process happens very often when p is low.

GPSR turns out to be the best routing protocol in terms of losses, as Fig. 6.7(d) shows, except for $p \geq 80\%$ where AODV outperforms GPSR. This is because GPSR does not use a buffer and in its original form (i.e. high p), so it drops a high number of packets if it does not find a next forwarding node. This protocol often chooses unreachable nodes due to obsolete neighbour information and other well-known routing problems [60]. As expected, we observe that low values of p result in high losses and vice versa. That is, a low p means that the packet will follow a path mainly formed by nodes randomly chosen, producing a longer path which increases losses. Conversely, a high p means that the packet will be forwarded according to the original scheme of the protocol, having shorter paths and lower losses consequently.

Figure 6.8(a) shows the percentage of anonymity as a function of the number of hops (h). We can see that the GPSR curve is closer to the single-hop lossless theoretical results, compared to the other protocols. This is very related to the number of hops, where GPSR has the closest number of hops to the theoretical expected values of anonymity. In Fig. 6.8(b) results show the percentage of anonymity as a function of the percentage of losses, where we can notice that GPSR-B increases the losses but the anonymity is the same in all the cases. AODV increases losses when gets a higher anonymity. GPSR losses are between 20% and 60% although if obtains a high anonymity.

6.5.3 Evaluation of results in urban scenarios

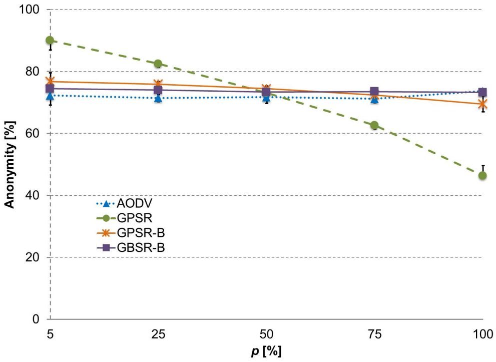
The third scenario represents a more realistic urban environment as it includes buildings that may block the transmission signal. Thus, according to our Greedy Buffer Stateless Routing- Building aware (i.e. GBSR-B), vehicles have less neighbours to select the next forwarding hop since those vehicles behind a wall are discarded as possible next hops. This will avoid sending packets to those vehicles which would produce their lost.

As in the previous scenario, each protocol itself already presents a certain level of anonymity, see Fig. 6.9(a) for p=100%. This is because not all the neighbours are in the same coverage range, so multipath routes may be needed to reach the AP. Due to multipath to achieve destination needed by the presence of buildings that block the signal, the AP will sometimes fail when guessing the source node (because the packet arrive from a several hops path) increasing the anonymity.

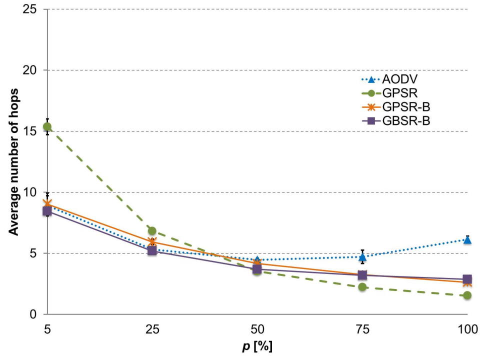
GBSR-B, GPSR-B and AODV show a higher anonymity when they operate without Crowd, i.e., $p \rightarrow 100$. This is because of its recovery path mechanism (based on a buffer). The fact that packets may be stored for a certain period of time contributes to maintain longer paths. As a result of this, it is more difficult for the AP to know who actually sent the packet. GPSR, however, has a recovery path mechanism (i.e., the perimeter mode) used when next forwarding decision fails. This mechanism has shown to be less efficient than the recovery mechanism (buffer) used in AODV [60].

For the average number of hops (see Fig. 6.9(b)) GPSR shows the closest results to the single-hop lossless theoretical results. The reason is that it is possible for a packet to get the destination after a high number of hops. This produces lower losses. GBSR-B and GPSR-B use a buffer which protects packets from losses. AODV also uses a buffer but has to find a new path every time the node has no route to destination, which may increase losses notably.

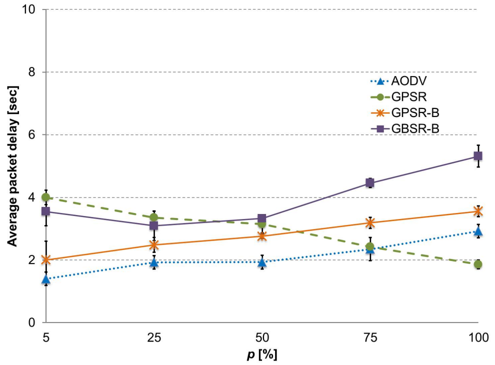
Fig. 6.9(c) shows the average delay. GBSR-B presents the highest delay when p=75 and p=100 because many packets could successfully be delivered, and many of these



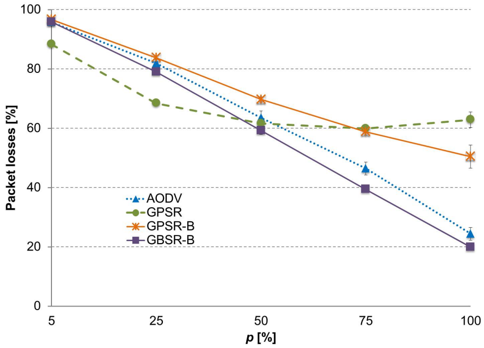
(a) Anonymity metric.



(b) Average number of hops.



(c) Average packet delay.

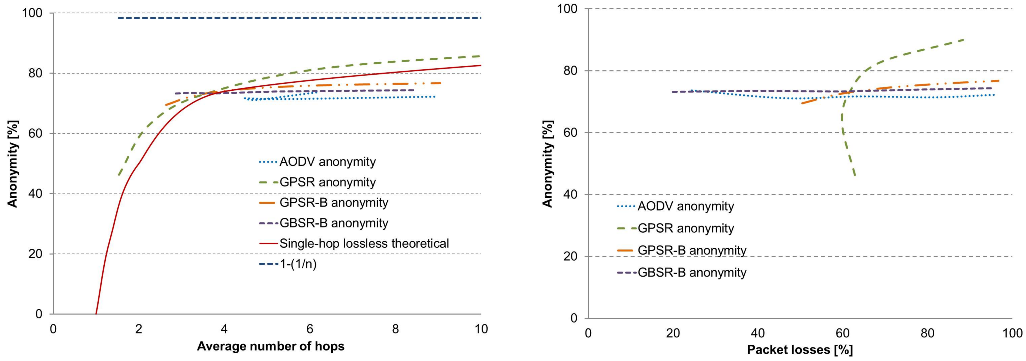


(d) Percentage of packet losses.

Figure 6.9: Urban scenario with buildings. AODV, GPSR, GPSR-B and GBSR-B metrics as a function of the Crowd probability (p) (CI 99%).

packet were some time in buffer. AODV presents the lower delay almost in all the points, except when p=100% where GPSR obtained the best results. This is because due to the buildings produces that more often a vehicle go out of transmission range of the neighbours and AODV has to find new paths after link breakages. GPSR-B shows a constant delay around 2 and 4 sec. in all cases, according to the behaviour of the number of hops (around 3 and 9 hops).

Regarding losses, AODV and GBSR-B have a logic tendency of lower losses for higher p values, and conversely lower p values produce higher losses, see Fig. 6.9(d). However, GBSR-B improves when p between 25% and 75%. GPSR-B presents also constant losses but higher than GBSR-B and AODV. GPSR is better than the other protocols except when p is higher than 50% when losses are higher.



(a) (b)

Figure 6.10: Percentage of anonymity as function of a) average number of hops and b) percentage of losses in the urban with buildings scenario.

Fig. 6.10(a) shows the percentage of anonymity as a function of the number of hops (h). We can see that the GPSR curve is closer to the single-hop lossless theoretical results, compared to the other protocols. This is because the number of hops is almost constant for every p value for AODV, GPSR-B and GBSR-B. The results in Fig. 6.10(b) shows the percentage of anonymity as a function of the percentage of losses. These results show that AODV and GBSR-B increases the losses but anonymity remains around 75%. GPSR losses are between 60% and 90% but has the highest anonymity. GPSR-B has around 75% of anonymity in all cases, but with 90% of losses in some cases.

6.6 Conclusions

In this chapter we have introduced the modifications to provide anonymity in a proactive routing protocol as AODV and location-based routing protocol as GPSR in vehicular ad hoc networks. To achieve this goal, we have adapted the Crowds mechanism used to provide anonymity. To analyse the functionality of Crowds over AODV and GPSR we evaluate urban vehicular scenarios. Also, we include the evaluation of the Crowds algorithm over our improvement protocols GPSR-B and GBSR-B, that are suitable for urban environments. We develop simulation scenarios based on an urban area of Barcelona, using the NCTUns 6.0 network simulator.

Our first contribution is a collaborative protocol that enables users to report traffic violations anonymously in multihop VANETs. Operating at the application layer, our approach is greatly inspired by the popular anonymous protocol Crowds. Our anonymous routing protocol depends on a forwarding probability that determines whether messages are routed at random or according to the routing protocol on which our approach builds. In terms of implementation, our approach only requires that users collaborate in the same way as they do when they route messages of other peers. Put differently, the proposed protocol could, in principle, be easily deployed and integrated into any multihop routing protocol.

Results show that GPSR in a unihop scenario works close to the analytical results providing a good level of anonymity. Also, we obtain that in a multihop scenario all protocols offer a certain level of anonymity due to the fact that they use several hops to get the destination, and not shared the same coverage range. We see in this case that packet losses increases. Finally, in the urban scenario one can see that our improvement GBSR-B outperforms the packet losses compared to all other protocols evaluated in urban scenarios. We can notice that the effect of packet losses due to the collisions contribute to decrease the anonymity level. Because packets that get destination using a high number of hops, increases anonymity. But if these packet are loss by collision and not achieve the destination, not contribute to increase the anonymity.

Another interesting finding is that the routing protocols per se, i.e., when they are not integrated into our anonymous routing protocol, do provide a reasonable degree of anonymity.

Several other attacks must be analysed, especially combined attacks intended to guess the identity of the node as the denied of service attack together with the malicious node collaborators. Mechanisms to prevent, react and mitigate these types of attack need to be formulated for having the Crowds with a reasonable level of anonymity security.

Chapter 7

VANET services in Smart Cities

7.1 Introduction

At the beginning of the development of vehicular technologies, the main goal was to have more efficient and safer roads. Nowadays, thanks to the huge development of wireless technologies and their application in vehicles, it is possible to use Intelligent Transportation System (ITS) that will change our way to drive, improving road safety, preventing car accidents, helping emergency services, saving pollution and reducing congestion. VANETs may soon allow vehicles to easily communicate among themselves and also with fixed infrastructure of cities and roads. This will not only improve road safety, but also raise new commercial opportunities such as infotainment for passengers.

The deployment of an efficient system to manage warning messages in VANETs has important benefits, from the perspective of both road operators and drivers. Efficient traffic alerts and updated information about traffic incidents will reduce traffic jams, increase road safety and improve the driving in the city. Furthermore, from the sustainable and economic perspective, real-time traffic alerting will reduce trip time and fuel consumption and therefore decrease the amount of CO_2 emissions [84].

In this chapter, a smart city framework is presented to offer some warning services in where Intelligent Traffic Lights (ITLs) set in the crossroads of a city are involved. These ITLs are in charge of gathering traffic information (e.g. traffic density) from passing vehicles, updating traffic statistics of the city and reporting those statistics to the vehicles, which will take driving decisions. Also, ITLs will send warning messages to vehicles in case of accidents to avoid further collisions.

The contribution of this chapter is supported by two publications: "Smart city for VANETs using warning messages, traffic statistics and intelligent traffic lights" published in the IEEE Intelligent Vehicles Symposium (IV 2012) [83] and "A distributed, bandwidth-efficient accident prevention system for interurban VANET's" published in the 4th IEEE International Conference on Smart Communication in Network Technologies (SaCoNeT 2013) [85].

7.2 Smart city projects

The European commission has developed a policy for sustainable mobility. The policy defines a political framework to ensure a high level of mobility, protection of humans and environment, technological innovation, and international cooperation. It was also defined the ambitious goal of reducing road fatalities by 50% by 2010. Hence, the European Union funds projects with this goals.

7.2.1 Living Labs

As we mentioned before, the special characteristics of VANETs make their evaluation a challenging task. Nowadays there are new environment of experimentation called Living Labs [86], that could be very helpful in the design and development of vehicular networks.

A Living Lab is a real-life test and experimentation environment where users and producers co-create innovations. The European Commission characterizes the Living Labs as Public-Private-People Partnerships (PPPP) for user-driven open innovation. Thus, a living Lab employs four main activities.

- *Co-Creation*: co-design by users and producers.
- *Exploration*: discovering emerging usages, behaviours and market opportunities.
- *Experimentation*: implementing live scenarios within communities of users.
- *Evaluation*: assessment of concepts, products and services according to socio-ergonomic, socio-cognitive and socio-economic criteria.

With this intention, many European and worldwide cities are currently being used as Living labs, such as the city of Barcelona. Many projects related to vehicular networks are being tested in these Living Labs around Europe.

7.2.1.1 ENoLL

The European Network of Living Labs (ENoLL) is the international federation of benchmarked living labs in Europe and worldwide. Founded in November 2006 under the auspices of the Finnish European Presidency, the network has grown in "waves" up to this day. To this date, 5 waves have been launched; resulting in over 270 accepted Living Labs.

The ENoLL international non-profit association, as the legal representative entity of the network, is headquartered in Brussels, at the heart of Europe [87].

Nowadays there are 21 effective members within the European Union, 4 of them in Spain (Andalusia, Catalonia, Valencia and Basque Country).

7.2.1.2 Living Labs Global

Living Labs Global [88] is a non-profit association based in Copenhagen (Denmark) with the objective to promote innovation in services and mobility in cities. It says that mobility is a paradigm shift in which the user, as a citizen, professional or visitor, is expecting public and private services to be tailored to their needs, delivered on demand, anywhere. At the same time, the global market for innovative services in cities is obscured by a lack of knowledge about other experiences, technologies and business ideas.

In 2003, Living Labs Global began as an idea to provide cities with a practical tool for service innovation to address urban challenges in fields such as transport, healthcare, sustainability, social services and tourism. Since then, Living Labs Global has emerged as an independent, sustainable global initiative receiving strong support from the cities, technology institutes, associations and innovative small and medium-sized enterprises that comprise its membership of more than 160 organizations, as well as the European Commission. Now is called CityMart.

7.2.1.3 22@ Living Labs

22@ [89] is a platform composed by companies, public and private institutions that origin and manage innovative processes of services and mobile technologies that involve companies interested in developing. This project is led by 22@Barcelona in collaboration with the Barcelona Digital Foundation and it belongs to the European Network of Living Labs (ENoLL).

7.2.1.4 ParkHelp Cities

ParkHelp [90] offers solutions with intelligent guidance systems designed for cities or areas that tell drivers where there are places available in parking areas (e.g. green or blue areas and special spaces), facilitating and optimizing the search time and their management. Set up in 2006 World pioneers developing IP connection products and applications. Present in more than 45 countries with an installed base of more than 200.000 parking spaces.

7.3 Management of traffic density

In this section, first we focus on the development of a smart city framework using the intelligent infrastructure developed in the streets, in our case Intelligent Traffic Lights (ITLs). Our proposal could easily be used by a traffic information centre to design an adaptive traffic light system similar to [91] and [92].

7.3.1 Smart city framework

The smart city framework that we have designed includes ITLs set in some of the crossroads. These ITLs collect real-time traffic data from the passing vehicles and calculate traffic statistics such as traffic density in the adjacent streets (between consecutive crossroads). At the same time, these ITLs can communicate the traffic information to passing vehicles and alert them with warning messages in case of accidents. These ITLs also form a sub-network that allows ITLs to share the collected information and calculate statistics of the whole city. Thus, vehicles are well informed of the traffic situation in the city.

In the smart city projected, blocks have a regular square design and buildings on its four sides. ITLs are responsible of managing the traffic of the vehicles, which form a VANET. These ITLs do not have to be located at each intersection. Within all the traffic lights that are traditionally located in a city, only a few will be replaced by ITLs. This is because each ITL covers a whole intersection and the 4 streets that converge on this intersection. ITLs are placed as shown in Fig. 7.1. To cover all this area the antenna pattern used is an omnidirectional propagation pattern. Therefore, each ITL receives data from all passing vehicles on its cover range (the four streets and the intersection). Not having an ITL on each intersection is more economic when implementing this framework.

It is assumed that vehicles have a GPS device, a driver assistant device, full map information of the city including the position of the ITLs. Thus, vehicles can easily select which is the nearest ITL. Every ad hoc node (i.e. ITLs and vehicles) set on the scenario was configured with Ad hoc On-demand Distance Vector (AODV) [44] routing protocol. AODV was selected because of its simplicity. Although it is well known that AODV is not suitable as routing protocol of general use in VANETs, there are some applications that might work well with AODV. The advantage of AODV is its simplicity and widespread use. The main drawback is that AODV needs end-to-end paths for data forwarding, which is difficult to handle because in VANETs end-to-end paths last not much due to high speeds of vehicles. Other routing protocols that use other strategies like greedy forwarding and geographical routing are more suitable for VANETs. For instance, GPSR (Greedy Perimeter Stateless Routing) [49] and GOSR (Geographical Opportunistic Source Routing) [71] have shown good performance in VANETs in terms of packet losses, but at the cost of increased delay. Nonetheless, for some applications that require a short delay AODV can perform well. In this chapter we are considering smart city services where vehicles send warning messages (weather conditions and traffic density) to the closest ITL, so it is not necessary to establish long paths that last long. Instead, vehicles need to establish very short paths (1-2 hops) to the nearest ITL. Besides, the communication must be quickly since vehicles move fast and the period in coverage range of the ITL is short. Thus, we can conclude that AODV is suitable for our purposes.

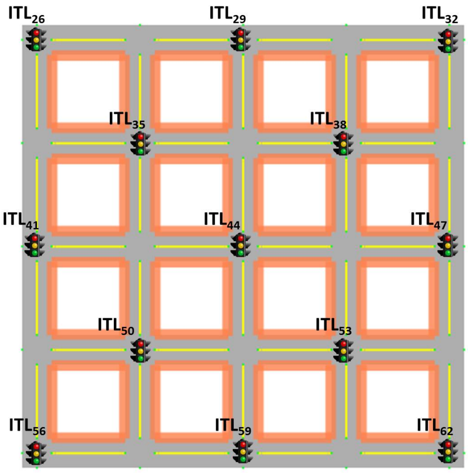


Figure 7.1: Intelligent Traffic Lights distribution.

7.3.2 Measure of the traffic density in a smart city

In this section we present the analysis of traffic density, although similar analysis could easily be done for other traffic statistics (e.g. number of passengers or trip time) [83].

The messages sent by each vehicle to an ITL include the type of message (a new message called Statistic Message, SM), the identification of the vehicle (C_i) sending the message, the current value of the number of neighbours (NoN_i) in its coverage range at that moment, the moment in which the message was sent (t_i) and the IP address of the ITL destination (ITL_i). This message is sent by the vehicles each 2 sec. This way, a car (v=40 km/h) sends 5 messages while it crosses a 100 m. street, which is enough to have good statistics of a street. The format of this message is shown in Table 7.1. The ITL will update the traffic statistics upon the reception of each new message, as it is explained below.

Fig. 7.2 shows the procedure of getting and sending traffic statistics from the vehicles to the ITLs. Each vehicle interchanges Hello Messages (HM) with its neighbours and

Table 7.1: Format information of message STAT.

Type	**Statistic Message (SM)**	**STAT**
stat_type	Traffic density (TD_{st})	0
stat_my_id	Car sending statistics	C_i
stat_neighbours	Number of neighbours (NoN)	NoN_i
stat_time	Time of statistics report	t_i
stat_dst	ITL IP address	ITL_i

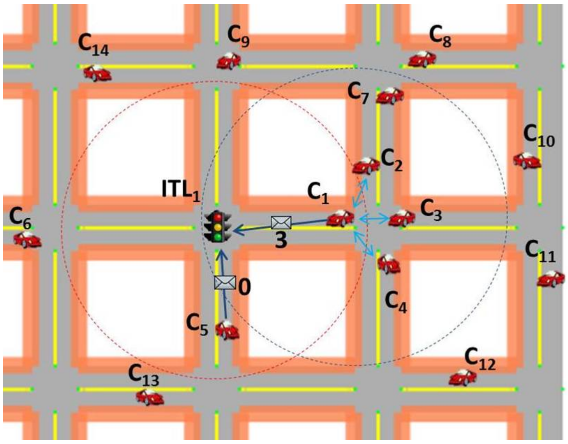


Figure 7.2: ITL obtaining traffic statistics in its intersection.

this way it knows the amount of vehicles in transmission range. Then, the vehicle sends a Statistic Message (SM) to the nearest ITL with the number of neighbours. For example, C_1 has three neighbours (C_2, C_3, and C_4). Notice that although C_7 is inside C_1's range they cannot establish any communication because of the buildings that represent obstacles for the communication. The car C_5 does not see any neighbour around so it sends a SM to the nearest ITL (i.e. ITL_1) with a zero on it.

ITL_1 will receive SMs and will update the traffic density statistics accordingly by using an Exponential Weighted Moving Average (EWMA) to average current and historical values. Then, ITL_1 will store the results properly and will share its statistics with the others ITLs in the city through the sub-network they form.

The day has been divided into five periods due to the usually variable traffic densities in a city throughout a day. Thus, every ITL updates the traffic density per periods: $TDst_{6-9}$, $TDst_{9-12}$, $TDst_{12-15}$, $TDst_{15-18}$, $TDst_{18-21}$. For example, $TDst_{6-9}$ gathers the average traffic density in the city, during week days, from 06:00 AM to 09:00 AM. The value $TDst_{6-9}$ will continuously be updated using Equation (7.1), where w is a small weight (e.g. w=0.25) to smooth out isolated deviations, $\overline{TDst}_{6-9,i}$ is the updated average in iteration i and $TDst_{6-9}$ is the last value received by that ITL. The same computation will be done for the other periods of the day.

$$\overline{TDst}_{6-9,i} = w \cdot \overline{TDst}_{6-9,i-1} + (1-w) \cdot TDst_{6-9} \tag{7.1}$$

The ITLs of the city share that traffic information and after that, each ITL will send back to each passing vehicle a message with the updated traffic statistics of the city on that period of time. With this information, the driver's assistant device can take proper trip decisions (e.g. avoiding congested roads). Also, data routing protocols may use that information to take suitable forwarding decisions (i.e. forward the packet

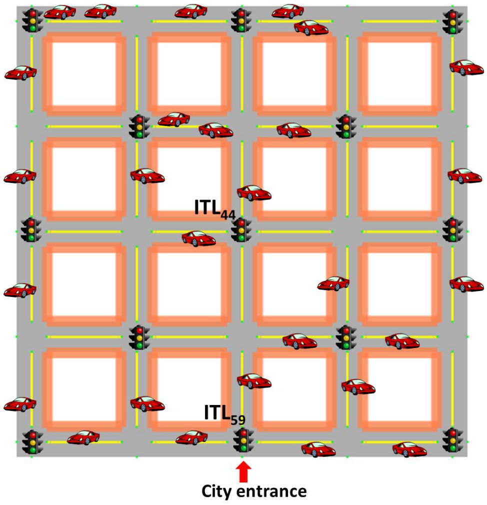


Figure 7.3: Traffic density simulation scenario.

through denser streets where there are more possible forwarding nodes).

7.3.3 Simulation results

To evaluate the operation of the traffic statistics system, we use a Manhattan scenario with streets that form 4x4 blocks (100 m x 100 m each), as depicted in Fig. 7.3. It has obstacles that represent buildings, and there are ITLs which are responsible to manage the traffic of the vehicles that form the VANET.

The simulation consists on a random number of smart vehicles moving around the city and establishing communications with the nearest ITL to send information of the current number of neighbours. Traffic statistics are updated as explained in previous section according to Equation 7.1. This data is sent by each vehicle every 2 sec. Every time an ITL receives data from a passing car it updates the statistics of traffic density on its surrounding area, stores it on an individual file and shares it with the rest of the ITLs of the city.

Fig. 7.4 shows the behaviour of the statistics collected by ITL_{44} (set in downtown, see Fig. 7.3). Here, simulations show 400 seconds (i.e. 15 h from 6 AM to 9 PM), so that 27 seconds in the simulations represents 1 h in real life. The results show the density of cars in downtown along the day. With this information drivers can obtain which are the roads more congested in each part of the city. Fig. 7.5 shows the results obtained by ITL_{59}, which is located in the entrance of the city. We can see the behaviour of the traffic flow in one day, where the more congested periods of time are between 12-15 PM. Streets are almost free between 6-9 AM and 18-21 PM.

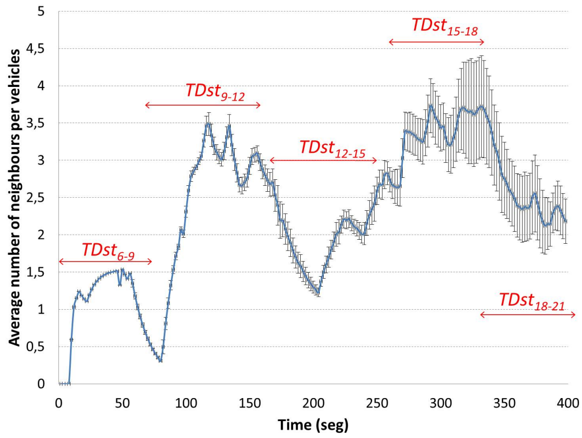


Figure 7.4: Average number of neighbours per vehicle measured by ITL_{44}, set in downtown.

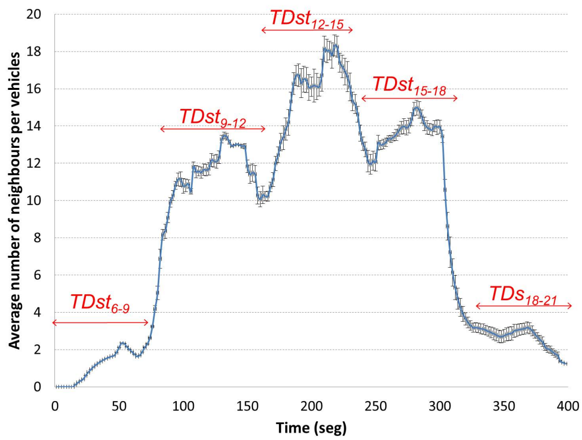


Figure 7.5: Average number of neighbours per vehicle measured by ITL_{59}, set in the city entrance.

7.4 Management of warning messages

In the promising smart cities of near future, communications between vehicles and the city will be constant, including V2V, I2I and V2I communications, by means of city infrastructure and Traffic Information Centres (TICs). Packets will contain different type of information and should be prioritized accordingly. For instance, packets containing information about an accident have to be prioritized over those containing other kind of data such as entertainment data.

Upon the reception of a warning message, a vehicle should consider its current distance to the initial source of the warning message and act consequently. For instance, a car being a long distance away from an accident will not act the same way (i.e. will not brake) when receiving a warning about the accident since it does not affect the immediate security of that car. Nonetheless, that warning message will inform the driver of that car (actually, the driver's assistant device), who may vary the trip plan consequently.

7.4.1 Warning messages

We have implemented a simple warning service to prevent further collisions by alerting drivers about accidents and dangerous road conditions. To achieve that goal, vehicles send short warning messages once one of the situations depicted in Table 7.2 has been detected. This information can be obtained from different sources. Regarding weather, data can be collected by a Wireless Sensor Network (WSN) that periodically transmits the weather conditions to the nearest ITL. Also, from small weather stations set in a few ITLs of the city. This information is spread through the city using the sub-

Table 7.2: Warning messages: Traffic and weather conditions.

Traffic density (2-bit)	Weather (2-bit)	Warning message: reduce speed
Free road segment	Sun	U
	Rain	85% · U
	Storm	65% · U
	Ice	40% · U
Semi-congested road segment	Sun	75% · U
	Rain	50% · U
	Storm	25% · U
	Ice	10% · U
Very congested road segment	Sun	50% · U
	Rain	40% · U
	Storm	30% · U
	Ice	10% · U
Accident	Sun	0
	Rain	0
	Storm	0
	Ice	0

U: Initial driver speed

network formed by the ITLs. Complementarily, the forecast proportioned by local public weather services could be used as well. The sub-network of ITLs could share that forecast information obtained from an Internet access point set in one of the ITLs. In case of accident, the vehicle itself (using sensors that detect that the car suffered an accident) communicates this situation to the closest ITL and to the neighbouring vehicles.

To know the traffic density, each ITL uses the statistics collected by the network of ITLs in the city (as explained in Section 7.3) regarding the average number of neighbours per vehicle in the streets along the day. Thus, depending on the average number of neighbours, two adaptive thresholds determine the traffic density of the road: free, semi-congested, very congested or accident (see Table 7.2).

We use a 4-bit field in the warning messages to code traffic density (2 bits) and weather information (2 bits). The warning message also includes a field with the location of the initial place of the warning message. Nearby vehicles that receive such message will reduce their speed depending on the warning message according to Table 7.2. For instance, in a very congested road with rain condition, warning messages inform nearby vehicles to reduce their speed to 40% of the initial driver speed (U in Table 7.2). The vehicle will brake accordingly to the situation received in the warning message, i.e., the traffic density status and the weather condition.

7.4.2 Improving the driver's reaction after accidents

To evaluate the operation of warning messages, an interurban scenario has been simulated to evaluate the benefits of the warning messages alerts for highway scenarios. Fig. 7.6 shows the simulation scenario. The cars in the simulation were represented using smart vehicles equipped with IEEE 802.11b interface on ad hoc mode. These vehicles are controlled by a program called *agent* (CarAgent.cc) that makes vehicles move through the city respecting streets, crossroads and traffic lights. This CarAgent is available with the NCTUns code.

As it was said previously, ad hoc nodes (i.e. ITLs and vehicles) use AODV. We simply modified AODV to be able to collect traffic statistics while establishing the routing paths. To do that, we use a modified RREQ messages that carry SMs (see Table 7.1).

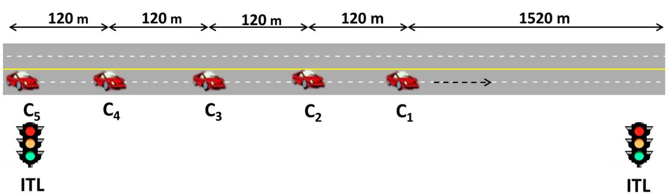


Figure 7.6: VANET smart road in a highway scenario.

Table 7.3: Simulation settings in the highway scenario.

Parameter	Value
Medium capacity	2 Mbps
Warning packet size	256 bytes
Transmission range (R)	200 m
Sensing range (S)	250 m
Distance between vehicles	120 m
Road length	2000 m
Average speed	120 km/h
Number of vehicles	5
TTL (warning messages)	7 sec.
Simulation time	100 sec

Table 7.4: Conditions simulated in the highway scenario.

Traffic conditions	Weather conditions	Period of time	Average vehicle velocity
Free segment	Sun	14 sec.	120 km/h
Accident	Sun	86 sec.	0 km/h

In this highway an accident will happen: the first vehicle in the queue (C_1 in Fig. 7.6) will crash. We will analyse how incoming vehicles react after this situation. ITLs send warning messages including weather and traffic information to passing vehicles. Due to cost issues there are only a few ITLs, so that warning messages are broadcast through the VANET using flooding dissemination. The main characteristics of the scenario are resumed in Table 7.3. Table 7.4 shows the traffic and weather conditions in the simulation: a highway in which the weather condition is *sun* and the traffic condition is *free segment* during 14 sec. Then, an accident takes place and the traffic condition changes to *accident*. Five vehicles participate in this scenario and the highest decrease in the vehicle's reaction time should take place in the last of the 5 vehicles in the queue (C_5 in Fig. 7.6). The reason is that without such a warning scheme, the last vehicle in the queue (i.e. C_5) will react after a considerable amount of time compared to the other vehicles ahead. Using this warning scheme, since the warning information travels fast hop-by-hop through the VANET from C_1 till C_5, the vehicle C_5 reacts sooner, only a little later than the vehicles ahead. This helps to reduce collisions and accidents.

The objective of these simulations is to evaluate if the use of ITLs reduce the driver's reaction time after accidents. According to the *Dirección General de Tráfico* (DGT) [93], responsible of the transportation policy in Spain, the average reaction time of a driver is 1 sec, so a car (v=120 km/h) before start braking still travels 55.89 m.

We define the driver's reaction time as the time elapsed since the accident moment

Table 7.5: Drivers's reaction time and distance travelled in the highway scenario.

	Reaction time	**Distance travelled due to reaction time (d_1)**	**Braking time**	**Distance travelled during braking time (d_2)**	**Total distance travelled (d_1+d_2)**
Vehicle 1 (ITS)	0.01 s	0.30 m	4.79 s	64.79 m	65.09 m
Vehicle 1 (no ITS)	1.00 s	33.30 m	4.79 s	64.79 m	98.09 m
Vehicle 2 (ITS)	0.05 s	1.70 m	4.28 s	57.91 m	59.61 m
Vehicle 2 (no ITS)	2.00 s	66.70 m	4.28 s	57.91 m	124.61 m
Vehicle 3 (ITS)	0.07 s	2.30 m	5.16 s	59.69 m	61.99 m
Vehicle 3 (no ITS)	3.00 s	100 m	5.16 s	59.69 m	159.69 m
Vehicle 4 (ITS)	0.31 s	10.30 m	4.63 s	62.51 m	72.81 m
Vehicle 4 (no ITS)	4.00 s	133.30 m	4.63 s	62.51 m	195.81 m
Vehicle 5 (ITS)	0.47 s	15.70 m	4.42 s	59.68 m	75.38 m
Vehicle 5 (no ITS)	5.00 s	166.70 m	4.42 s	59.68 m	226.38 m

to the time the vehicle starts to react, i.e., to brake, due either to the driver's reaction (no intelligent infrastructure) or to the own vehicle's reaction (using intelligent vehicle infrastructure). In Table 7.5 the differences between a highway using this intelligent traffic system (ITS) and a traditional highway (no ITS) can be appreciated. The first column shows the reaction time after the accident. It can be seen that this time increases as farther is the vehicle from the accident. It can also be observed how this time is drastically reduced in all vehicles when using intelligent infrastructure. For instance, the last vehicle in the queue (C_5) reduces its reaction time from 5 sec. to 0.47 sec. The second column represents the distance travelled during this reaction time, i.e., during the interval in which the accident has already been produced but the driver does not react yet. As observed, this reduction in the distance travelled is proportional to the reduction of time. The third column shows the time during which the driver brakes

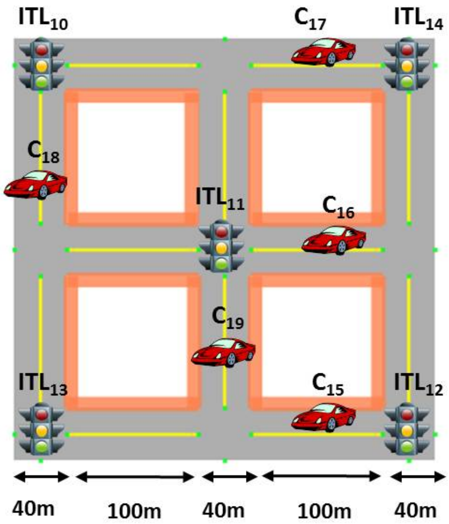


Figure 7.7: Simulation of a car accident in a downtown scenario.

from the moment s/he knows that conditions changed until it reaches the recommended velocity (till stop in case of accident). This time does not change using or not using intelligent infrastructure. Therefore, the distance travelled due to braking time does not change, as shown in the fourth column. The last column shows the total distance elapsed since the start of the maneuver to stop the vehicle. It can be appreciated that the maximum distance is on vehicle number 5, from 226.38 m to 75.38 m when using intelligent infrastructure.

Also, we evaluate an urban scenario to show how the vehicles react under different traffic and weather conditions. Fig. 7.7 shows a neighbourhood of the city where a car accident will happen. The simulation recreates a Manhattan 280 x 280 m^2 scenario. The length of the streets is 100 m, and the size of every cross is 40 m. These values were chosen to emulate the regular downtown streets in the city of Barcelona. In the scenario there are 5 vehicles and 5 ITLs. During the simulation, vehicle C_{18} has an accident and remains broken close to the ITL_{11} situated in the centre, see Fig. 7.7. Vehicles C_{15}, C_{16}, C_{17} and C_{19} are all travelling towards ITL_{11}. In this simulation it is shown how the use of ITL helps to avoid collision among the other vehicles and the broken vehicle, thanks to our warning scheme that makes them brake beforehand. Table 7.6 summarizes the traffic and weather conditions during the simulation.

The accident will occur in the second 30. The traffic lights ITL_{10}, ITL_{12}, ITL_{13} and ITL_{14} will send messages of *good weather conditions* and *free traffic segment* during the 80 second of this simulation. The traffic light number ITL_{11} will send during 30 seconds messages of *good weather conditions* and *free traffic segment*. After that, ITL_{11}

Table 7.6: Traffic and weather conditions during the simulation of the downtown scenario.

Traffic conditions	**Weather conditions**	**Period of time**	**Average vehicle velocity**
Free segment	Sun	30 sec.	40 km/h
Accident	Sun	50 sec.	0 km/h

Table 7.7: Simulation settings in the downtown scenario.

Parameter	**Value**
Medium capacity	11 Mbps
Packet size	256 bytes
Transmission range	130 m
Carrier sense range	180 m
Simulation time	80 sec.
MAC specification	IEEE 802.11b
Area	320 x 320 m^2
Maximum Average speed	40 km/h
Number of nodes	5 ITLs and 5 vehicles
Mobility model	CarAgentMod (NCTUns)
Routing protocol	AODV

Table 7.8: Driver's reaction time and distance travelled in the downtown scenario.

	Use of ITLs	**Non use of ITLs**
Driver's reaction time	0.084 s	1 s
Distance travelled till reaction	0.93 m	11.11 m
Braking period of time	1.355 s	1.355 s
Distance travelled during braking	7.52 m	7.52 m
Total distance travelled	8.45 m	18.63 m

will send *good weather conditions* and *accident* during the next 50 sec. Each of the ITLs sends these packets to the vehicles in the four streets that go from the crossroads where they are located to the next 4 closest crossroads.

ITLs will broadcast 256 bytes messages every 0.2 seconds (i.e. 5 messages per second) with information about traffic conditions, weather conditions and accident warnings. Vehicles move randomly through the streets at an average velocity of 40 km/h (it automatically decreases when approaching an intersection). Simulation settings are summarized in Table 7.7.

Using our framework the driver's reaction time was 0.084 seconds, which represents that the distance travelled will be reduced to 8.45 m. Table 7.8 shows the time and distances that a vehicle, in average, travels with and without the use of our accident warning scheme. In this case, it can be appreciated that the safety distance from the car to the obstacle has been reduced around 55% from 18.63 m without the use of ITLs to 8.45 m using them, which increases road safety notably.

With these results we confirm that the use of smart roads and vehicles reduce the vehicle's reaction time after an accident to avoid further collisions with other arriving vehicles. Thus, we can conclude that our scheme improves road safety notably.

7.5 Conclusions

In this chapter we summarize the design of a smart city framework for VANETs that includes intelligent traffic lights (ITLs) and provides some services such as the transmission of warning messages and the computation of traffic statistics. We have implemented the framework in the NCTUns 6.0 simulator [63]. Simulation results show that the use of ITLs in smart cities can not only improve road safety as in downtown cities or highways but also the driver's quality of life. We have explained how the ITLs gather traffic and weather conditions of the roads and how they update those statistics. The goal is that the driver's assistant device can take proper trip decisions, for instance to avoid congested roads, and therefore reduce the trip time and pollution as well. Besides, our smart city framework includes warning messages sent by possible broken vehicles to make approaching vehicles brake beforehand and thus avoid more collisions. Simulation results show the effectiveness of this scheme, reducing the distance to brake and the driver's reaction time.

Another service that could be implemented in a smart city is a smart parking service. ITLs could communicate to passing vehicles indicating where are the free parking spots in the city. With this information, the driver assistant device could indicate the driver where free spots are located. This system could use a WSN to get the data about free parking spots and communicate it to the nearest ITLs. The ITLs could share that information though the sub-network they form. This would save trip time, petrol and CO_2 as a consequence, which helps to have sustainable smart cities.

Also, statistics collected by the ITLs can improve data routing protocols selecting the path that offers a higher chance to forward a packet to the destination successfully.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

The main objective of the research work carried out during this PhD thesis was to develop a framework in order to improve vehicular communications in urban scenarios.

Due to the changing nature of the Vehicular Ad hoc Networks (VANETs), it was necessary to take into account several characteristics of the behaviour of the vehicles to improve the correct communications of the nodes. The high speed of the nodes, the unpredictable scenario, the quickly change of the neighbouring, the fast changes of topology, etc., are some of the main issues present in VANETs. All these issues have been considered in our design of a proper routing protocols for vehicular scenarios.

We have analysed the main issues in vehicular environments and the proposals published in the specialized literature are with the goal of developing a multi-metric routing protocol that includes improvements to reduce the packet losses. It is well known that in vehicular networks the communication link between two nodes lasts only a few seconds. Therefore, the best forwarding decisions are taken hop-by-hop. A good forwarding decision may result in a high number of packets delivered to destination. We took GPSR (Greedy Perimeter Stateless Routing) [49] as a base over which we developed our proposals, since it is a geographic routing protocol.

Also, we have evaluated the challenge issue of providing QoS and anonymity in these networks. QoS is needed in some services that could be present in vehicular environments, like multimedia and infotainment. Anonymity is also needed because in vehicular communications there is a lot of data exchange, and nowadays it is important to maintain a certain security in personal interchange of information.

As a result of our research work, we have developed several proposals. We can list the main contributions of this research work as follows:

- Firstly, we improved the way in which GPSR takes decisions by including a buffer solution to store packets when no neighbour is around. This increases the probability to find in a future a good forwarding node or the final destination. Also, it includes a map-aware functionality, which gives knowledge of the environment to vehicles. Therefore, vehicles are not allowed to send packets to vehicles behind walls or out of the line of sight (LOS). We called our first proposal as GBSR-B [59] which gave us a considerable improvement in packet losses in all urban scenario with the price of slightly increasing delays because some packets will be stored in the local buffer. Our proposal is an excellent option in urban networks with delay tolerant services. Although slightly increasing in the average end-to-end delay, GBSR-B offers a considerable low percentage of losses.

- Secondly, we tackled the issue of providing communications in VANETs with a certain level of QoS, in order to improve multimedia services or Infotainment. We included an available bandwidth estimation (ABE) [9] algorithm in GPSR and AODV to evaluate the original ABE in vehicular environments. ABE was originally designed for Mobile Ad hoc Networks (MANETs). Our bandwidth estimator evaluates hop-by-hop the available bandwidth and only allows to establish the communication if the link can provide enough bandwidth to ensure the required bandwidth. Finally, ABE was included as a metric in our final routing proposal.

- During the analysis of the ABE, we improved some of the parameters in its mathematical expression and we proposed a new model to calculate the probability of packet losses computed more accurately for vehicular networks. Our new function takes into account not only the packet size, but also the number of nodes in the scenario and the speed of the vehicles. The reason was the need to develop a proposal which is able to adapt to the changing scenarios present in urban environments. Finally, we made a measurement of the probability of packet losses and of *hello messages* during the simulation, obtaining a higher level of accuracy using our expression than using the original ABE designed for MANETs.

- Thirdly, we proposed and evaluated a routing protocol that includes an anonymity communications scheme based on the Crowds algorithm [3]. We adapted the Crowds algorithm to our proposal GBSR-B to hide the real emisor of a packet to the final destination. This way, forwarding decisions are based on a random selection of the neighbours in transmission range. The goal was that the destination will not know who actually sent the packet in the first moment. After several tests, we concluded that GBSR-B reduces the packet losses compared to all the other protocols that we have evaluated in urban scenarios.

- We also proposed a new routing protocol, called Multimetric Map-aware Routing protocol (MMMR) for VANETs that includes four metrics as the base to take hop-by-hop forwarding decisions. After the analysis of several proposals we developed an algorithm that includes four metrics and a global average score value that allows us to select the best next hop among all the neighbours in transmission range.

We made the analysis based on the importance of each metric independently and after that making several combinations of the four metrics used. Simulation results shows the improvement of our proposal.

The results of our evaluation show that our MMMR improves the results in terms of packet losses, and obtains a considerable low end-to-end packet delay compared to other routing protocols. Also, we proved that considering the four metrics in the forwarding decision is better than considering each metric independently.

- And finally, we presented two services that vehicular networks can offer in the challenging concept of the smart cities. First, the management of warning messages to reduce the distance to brake and also the driver's reaction time, which produces a considerable reduction of the time of reaction when an accident happens. Consequently, the number of accidents in roads is reduced. Also, we included the feature of the management of the vehicles' density in the streets so that the driver's assistant device can take proper trip decisions. For instance, to avoid congested roads and therefore reduce the trip time and pollution as well.

  We obtained that using intelligent traffic lights (ITLs) the driver reaction could be reduced from 1 second to 0.084 second, avoiding thus considerable future crashes. Also the use of a real and accurate density statistics improves data routing protocols by selecting the path that offers a higher chance to forward a packet to the destination successfully. The proposal would save trip time, petrol and CO_2 as a consequence, which helps to have sustainable smart cities.

8.2 Research papers published as a result of the thesis work

In this section, we list the publications that have been generated from the research work done in this thesis. They can also be downloaded from:

http://sertel.upc.edu/users/ctripp

International Journals and JCR Publications

- [81] D. Rebollo-Monedero, J. Forné, E. Pallarès, J. Parra-Arnau, **C. Tripp**, L. Urquiza, M. Aguilar, "On Collaborative Anonymous Communications in Lossy Networks", Security and Communication Networks, Special Issue on Security in a Completely Interconnected World, ISSN: 1939-0114, 2013. (IF 2011 =0.414, Q4). DOI: http://dx.doi.org/10.1002/sec.793.

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for Anonymous Reporting in Vehicular Ad Hoc Networks", Computer Standards & Interfaces, ISSN: 0920-5489, 2013. (IF 2011 = 1.257, Q2). *Under second review.*

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International Conferences

- [65] **C. Tripp-Barba**, M. Aguilar Igartua, L. Urquiza Aguiar, A. M. Mezher, A. Zaldívar, I. Guérin-Lassous, "Available Bandwidth Estimation in GPSR for VANETs", 3rd ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet'13), November 2013, Barcelona, Spain. *Submitted.*

- [85] E. Garcia-Lozano, **C. Tripp Barba**, M. Aguilar Igartua, C. Campo, "A distributed, bandwidth-efficient accident prevention system for interurban VANETs", 4th IEEE International Conference on Smart Communication in Network Technologies (SaCoNeT'13), June 2013, Paris, France. *Accepted and publication pending.*

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- [83] **C. Tripp Barba**, M. A. Mateos, P. Regañas, A. M. Mezher, M. Aguilar Igartua, "Smart city for VANETs using warning messages, traffic statistics and intelligent traffic lights", IEEE Intelligent Vehicles Symposium (IV'12), June 2012, pp. 902-907, ISBN: 978-1-4673-2117-4, Alcalá de Henares, Madrid.

- [94] **C. Tripp Barba**, K. Ornelas, M. Aguilar Igartua, "Performance evaluation of a Hybrid Sensor and Vehicular Network to improve road safety", 7th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PEWASUN'10), October 2010, pp. 71-78, ISBN: 978-1-4503-0276-0, Bodrum, Turkey.

National Conferences

- [95] A. M. Mezher, **C. Tripp-Barba**, L. Urquiza Aguiar, M. Aguilar Igartua, I. Martín, "Optimization of the path selection in a Game-theoretic routing protocol for video-streaming services over Mobile Ad hoc Networks", XI Jornadas de Ingeniería Telemática (JITEL'13), October 2013, Granada, Spain. *Submitted.*

- [96] **C. Tripp Barba**, M. Aguilar Igartua, "Contribution to develop a communication framework for vehicular ad-hoc networks in urban scenarios", Forum on PhD Research Information and Communication Technologies (ICT'12), October 15, 2012, pp. 47-48, ISBN: 978-84-615-9915-8, Barcelona, Spain.

- [97] **C. Tripp Barba**, K. Ornelas, G. Díaz-Delgado, M. Aguilar Igartua "Evaluación de prestaciones de una red híbrida vehicular y de sensores para mejorar la seguridad vial", IX Jornadas de Ingeniería Telemática (JITEL'10), September 29 - October 1, 2010, pp. 199-205, ISBN: 978-84-693-5398-1. Valladolid, Spain.

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8.3 Future work

Vehicular Ad hoc Networks is a field that offers a lot of current and future research. In the development of this thesis several issues emerged which deserve further research in a future. The ones we consider most relevant are the following:

- An important future work is the evaluation of all our proposals using the MAC IEEE 802.11p specification, which is specially focused on VANETs. Nowadays, it is already available in some simulators as NS-2 and Veins. It would be interesting to compare our results to the results obtained using this standard.

- Realistic scenarios are an important issue in vehicular networks. It would be interesting to carry out the implementation and performance evaluation of other mobility models closer to reality to include more characteristics of the real world, as real maps for instance.

- The development of a new mathematical model to obtain the final value of the multimetric score to take the forwarding decision using machine learning techniques. This way, we would have a self-configuring vehicular network that adapts itself using feedback information of the VANET.
- Another field of the vehicular network research is the modeling of the physical level to provide power control in the communications. That is, depending on the distance of the communicating node, the transmission power could be higher or lower. Actually, this feature works in current wireless cards.
- Development of an approach to offer Infotainment (i.e. video streaming) in VANETs.
- A good data dissemination model could be implemented to improve the spread of warning messages to reduce accidents and increase road security.

Appendix A

Network simulators for VANETs

Currently, Vehicular Ad hoc Networks (VANETs) are gaining a lot of attention by the research community and they are seeing a fast development. Researchers have made VANET simulation software to allow the study and evaluation of the several improvements and applications focused on vehicular networks. VANET simulation is fundamentally different from MANET (Mobile Ad hoc Network) simulation. In VANETs, the vehicular environment has new issues and requirements, such as constrained road topology, multi-path fading and roadside obstacles, traffic flow models, mobility models, changes of vehicular speed, traffic lights, traffic congestion, driver's behavior, etc. Network simulators allow researchers to study how the network would behave under different conditions. In this appendix we summarize the main characteristics of some existing simulators used by researchers.

A.1 OPNET

OPNET (Optimized Network Engineering Tools) [101] is a commercial network simulator that provides high fidelity modeling, simulation, and analysis of a broad range of wireless networks. Technology developers leverage advanced simulation capabilities and rich protocol model suites to design and optimize proprietary wireless protocols, such as access control and scheduling algorithms. Simulations incorporate motion in mobile networks, including ground, airborne and satellite systems. OPNET supports any network with mobile devices, including cellular (GSM, CDMA, UMTS, IEEE 802.16 WiMAX, LTE, etc.), mobile ad hoc, wireless LAN (IEEE 802.11), personal area networks (Bluetooth, ZigBee, etc.) and satellite.

There are three basic phases of the OPNET deployment process. First, choose and configure node models to use in simulations, such as a wireless node, trajectory, and so on. Second, build and organize the network by setting up connections for different entities. Third, select the desired statistics (local or global) to collect during the simulation.

OPNET includes simple mobility options such as: a) *Random Drunken Model*: at each intersection, the vehicle randomly selects from four directions or chooses to remain stationary. b) *Random Waypoint Model*: the vehicle randomly picks a destination. Upon reaching the destination, the vehicle pauses a random amount of time and the selects a new destination. c) *Trace*: vehicle movement is based on an imported trace file.

It uses a network configuration file where is specifies all of the network related parameters, as node, routers, applications, protocols, radios, etc. The global parameters define the simulation time, coordinate system, random number seed, protocol stack, etc. In addition to the GUI-based output, the simulation produces a statistic file, which contains all the statistic generated from the simulation run.

A.2 GloMoSim and QualNet

GloMoSim (Global Mobile Information System Simulator) [40] [102] it was developed by the Parallel Computing Laboratory in University of California, Los Angeles (UCLA) in 1999. Earlier GloMoSim had no support for GUI but now it includes a java based front end as well.

This simulator was coded in Parsec and all new protocols must be defined in Parsec as well. Parsec is a C-based simulation language, developed also by the Parallel Computing Laboratory, for sequential and parallel execution of discrete-event simulation models. It can also be used as a parallel programming language.

Another feature is that it has the ability to run on SMP (Shared-Memory symmetric Processor), which allows that memory is simultaneously accessible by all programs and helps to divide the network into separate modules each running as a distinct process. This reduces the load on CPU by dividing its workload. Because of these multi-tasking features, the user is able to simulate tens of thousands of nodes in a single simulation.

This simulator is packaged with libraries for simulating multiple mobility models. Regarding radio propagation models, GloMoSim supports TwoRayGround and Free Space models. GloMoSim was designed to support millions of nodes in a single simulation using parallelism techniques. Node aggregation has always been the bottleneck in most simulations but this simulator was the first one to implement it successfully. It also has the ability to support layer aggregation.

The input files of this simulator are nodes.input, mobility.in, app.conf, and config.in. The main configuration parameters for setting up a scenario are defined in config.in, which specifies the mobility, simulation time, radio-related parameters, all layers' protocols, and the application configuration. The file node.input specifies the nodes' topology (coordinates of each node). The file app.conf specifies the applications that generate traffic, and mobility.in specifies the trace, or trip, of nodes. An output file

GLOMO.STAT is generated at the end of a simulation, which contains statistical information for each node at a certain layer.

GloMoSim version 2.0 was released in 2000 and after that, PARSEC stopped working on freeware software and released a commercial version of GloMoSim called QualNet [38].

QualNet includes a sophisticated GUI for setting up and running simulations, and provides a large set of wireless physical and MAC layer models. It also includes the following mobility models: Group mobility, Pedestrian mobility and Random Waypoint. QualNet is available for both Windows and Unix/Linux platforms.

A.3 NS-2 and NS-3

In 1989, NS-2 [37] appeared as a network simulator that provided significant simulation of transport, routing, and multicast over wired and wireless networks. NS-2 was developed by the Information Sciences Institute of the University of Southern California.

Although the core of NS-2 is written in C++, but users interact with NS-2 by writing Tool Command Language (TCL) scripts. These scripts should contain all of the commands needed for specifying the simulation (e.g. setting up the topology, specifying wireless parameters, and so on).

There are implementations of several mobility models available for NS-2, including Random Trip Mobility and Semi-Markov Smooth Mobility. NS-2 is packaged with a bundle of rich libraries for simulating wireless networks. All the mobile nodes in NS-2 quickly assume that they are part of ad-hoc network and the simulation of mobile nodes connected with infrastructure networks is not really possible. To simulate a wireless node, the physical layer, the link layer and MAC protocol are all included at the same time. But despite this, NS-2 is unable to simulate multiple radio interfaces. Moreover NS-2 has unrealistic models for wireless channel, which results in a biased radio propagation. For wireless simulation, NS-2 supports only free space and two ray ground reflection models and cannot simulate path loss, multi-path fading and shadowing phenomena.

Besides, NS-2 only supports bi-directional (radiates or receives most of its energy in two directions) and omni-directional (radiates signal equally in all directions) antennas for signal propagation and waypoint mobility model for node movement. When simulating wireless networks using NS-2, the nodes need to be programmed manually to sense and transmit data among each other. There is no built-in scanning facility available to sense other nodes that are floating around. Another constraint associated with NS-2 is that it cannot be extended to simulate a large mobile network.

However, some features made NS-2 to be the most widely used network simulator: it is open-source, many of the standard networking components and protocols are available and there is a well documented code base. On the other hand, this simulator is not easy to use because it has been extended by many developers so the architecture of NS-2 is very complex.

NS-3 [103] is open-source, and the project strives to maintain an open environment for researchers to contribute and share their software. Is not an extension of NS-2, but also it is written purely in C++. NS-3 does have new capabilities (such as handling multiple interfaces on nodes correctly, use of IP addressing and more alignment with Internet protocols and designs, more detailed 802.11 models, etc.

A.4 OMNeT++

OMNeT++ [104] is an open-source simulation environment, free for academic and non-profit use, and it is a widely used platform in the global scientific community. The primary simulation applications are Internet simulations, mobility, and ad hoc simulations. This simulator has a component-based design, meaning that new features and protocols can be supported through modules. OMNeT++ supports network and mobility models through the independently developed Mobility Framework and INET Framework modules.

OMNeT++ simulations consist of simple modules that implement the atomic behaviour of a model, e.g. a particular protocol. Multiple simple modules can be linked together and form a compound module. This linking and the set-up of the network simulation takes place in NED, OMNeT++'s network description language. NED is transparently rendered into C++ code when the simulation is compiled as a whole. Moreover, NED supports the specification of variable parameters in the network description: for example, the number of nodes in a network can be marked to be dynamic and later on be configured at runtime.

Simulation design in OMNeT++ is GUI-based, and output data can be plotted through the GUI as well. Although OMNeT++ is not a network simulator itself, it is currently gaining widespread popularity as a network simulation platform in the scientific community as well as in industrial settings, and building up a large user community. OMNeT++ runs on Linux, Mac OS X, other Unix-like systems and on Windows (XP, Win2K, Vista, 7).

A.5 Veins 2.0

Veins (Vehicles in Network Simulation) [105] is another simulator that couples a mobility simulator with a network simulator. In Veins, SUMO is paired with OMNeT++ by extending SUMO to allow it to communicate with OMNeT++ through a TCP connection.

In order to create a bidirectional communication between the two simulators, OMNeT++ has also been extended by adding a module that allows all participating nodes (vehicles) to send commands via the established TCP connection to SUMO [33]. In this case, the two extensions represent the interface between the network simulator and the mobility simulator. Thus, the network simulator can react to the received mobility trace from the mobility simulator by introducing new nodes, by deleting nodes that have reached their destination, and by moving nodes according to the instructions from the mobility simulator.

The Veins project team have announced Veins 2.0, the latest version of their vehicular network simulation framework for OMNeT++. Veins is an open source Inter-Vehicular Communication (IVC) simulation framework composed of an event-based network simulator and a road traffic micro-simulation model, containing numerous improvements and new features.

Veins 2.0 now makes use mobility models, multi-path propagation, obstacle-caused fading in vehicular networks, as well as PHY and MAC layer modules. Veins 2.0 features dedicated models of IEEE 802.11p and IEEE 1609.4 DSRC PHY and MAC layers, including Access Categories for QoS, Wave Short Message (WSM) handling, and beaconing WAVE service announcements, as well as multi channel operation, i.e. the periodic switching between the Control Channel (CCH) and Service Channels (SCHs). The IEEE 1609.4/802.11p MAC behaviour has been further optimized (minor bug fixes and performance tweaks).

Veins 2.0 is based on pure Open Source software offering unrestricted extensibility, relies on SUMO, a trusted vehicular mobility model and implementation by the Transportation and Traffic Science community.

A.6 SWANS and SWANS++

SWANS (Scalable Wireless Ad hoc Network Simulator) [106] was developed to be a scalable alternative to NS-2 for simulating wireless networks. SWANS is organized as independent software components that can be composed to form complete wireless network or sensor network configurations.

Based on comparisons of SWANS, GloMoSim, and NS-2, SWANS was determined to be the most scalable and the most efficient in memory usage with the fastest runtime. Along with better performance, SWANS delivered similar results as NS-2, at least for the network components that were implemented in both.

The input for SWANS is a Java file that creates the nodes and specifies how these nodes should move (the node movement scenario) and how they should communicate (the communication scenario). The user can select any of the ready-made applications in SWANS and associate it with any node(s) to execute it at the node application layer. Also, SWANS gives the user the flexibility to build a custom application and execute it at the application layer of any node.

SWANS++ [107] extends the network simulator SWANS by adding a GUI to visualize the scenario and a mobility model, STRAW (STreet RAndom Waypoint), for the vehicles movement in street scenarios. STRAW uses the simple random waypoint mobility model, but it restricts the vehicles movement to real street boundaries, loaded from TIGER/Line data files. TIGER/Line data files contain features such as roads, railroads, rivers, as well as legal and statistical geographic areas.

STRAW consists mainly of three components: intra-segment mobility, intersegment mobility, and route management and execution. In intersegment mobility, the vehicles move according to a car-following model and change their speed only in certain situations. For intersegment mobility, according to the system design, there is either a traffic control sign or a stop sign at each intersection that forces the vehicle to alter its speed. The mobility model implemented in STRAW (and therefore, SWANS++) does not support lane changing. The route management and execution (RME) module is responsible for determining the vehicles routes during the simulation.

SWANS++ is a tightly integrated simulator, but it does not provide feedback between the mobility and networking modules.

A.7 TraNS

TraNS (Traffic and Network Simulation Environment) [30] can be considered as the first pure VANET simulator. It was the first work to combine a network simulator, NS-2, with a vehicular mobility simulator: SUMO, and to provide feedback from the network simulator to the mobility simulator. TraNS can operate in two modes: network-centric mode and application-centric mode. In the network-centric mode, there is no feedback provided from NS-2 to SUMO, so the vehicles mobility trace file can be pre-generated and fed to the network simulator later. The link between the two simulators in this case is done through a parser that analyses the mobility trace file generated by SUMO and converts it to a suitable format for NS-2. In the application-centric mode, the feedback between NS-2 and SUMO is provided through an interface called TraCI. In this mode, the two simulators (SUMO and NS-2) must run simultaneously. TraCI achieves the link between NS-2 and SUMO by converting the mobility commands coming from NS-2 to a sequence of mobility primitive commands such as stop, change lane, change speed, and so on that can be sent to SUMO. As both simulators are running separately at the same time, the two-way communication in application-centric mode uses two separate events queues.

A.8 NCTUns

NCTUns (National Chiao Tung University Network Simulator) [7] [63] implements two-way communication with a single events queue. NCTUns 1.0 was developed only as a network simulator, but the most recent version, NCTUns 6.0, integrates some traffic simulation capabilities, such as designing maps and controlling vehicles mobility. Also, NCTUns includes a GUI to aid in the design process of the maps. The supported vehicular movement has two modes, pre-specified and autopilot. In the pre-specified movement mode, the scenario designer specifies the moving path and the speed for each vehicle. In autopilot mode, the scenario designer specifies the following parameters for each vehicle: initial speed, maximum speed, initial acceleration, maximum acceleration, maximum deceleration, and so on. Then, the autopilot selects the best route to navigate in the map and it is also capable of performing car following, lane changing, overtaking, turning, and traffic light obeying.

The NCTUns network simulator has many useful features: it directly uses the real-life Linux TCP/IP protocol stack to generate high-fidelity simulation results, it provides a highly-integrated and professional GUI environment and its simulation engine adopts an open-system architecture and is open source. Moreover, it simulates various important networks: Ethernet-based fixed Internet, IEEE 802.11(b) wireless LANs, mobile ad hoc (sensor) networks, GPRS cellular networks, optical networks (including both circuit-switching and burst-switching networks), IEEE 802.11(b) dual-radio wireless mesh networks, IEEE 802.11(e) QoS wireless LANs, tactical and active mobile ad hoc networks, IEEE 802.16(d) WiMAX wireless networks (including the PMP and mesh modes), DVB-RCS satellite networks, wireless vehicular networks for Intelligent Transportation Systems (including V2V and V2I), multi-interface mobile nodes for heterogeneous wireless networks, IEEE 802.16(e) mobile WiMAX networks, IEEE 802.11(p)/1609 WAVE wireless vehicular networks, various realistic wireless channel models, IEEE 802.16(j) transparent mode and non-transparent mode WiMAX networks, etc.

On the 1st of December of 2010, the commercial version of NCTUns was announced to all the users of the simulator via e-mail; it will be called EstiNet [108]. According to its developers, EstiNet is launched to provide better quality, functionality, performance and support.

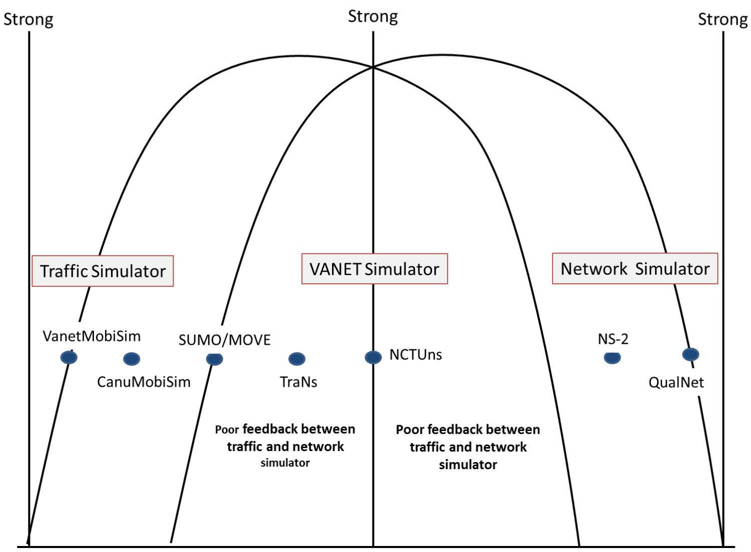

Figure A.1: Compromise between networks simulators and traffic simulators.

A.9 Conclusion

There is currently no standard or preferred simulator for evaluating proposals done in the vehicular networking research. Most often, researchers have combined existing mobility simulators with existing networks simulators by generating mobility traces that could be used in network simulators.

Of all the above mentioned simulators, NCTUns was chosen to perform the tests of this thesis. The main reason to use NCTUns was the fact that it is a free of use open-source tool and the capabilities for wireless vehicular network research that the simulator provides. Moreover, the user does not need to deal with complex coding thanks to the powerful GUI support provided by this simulator. Using the GUI tool, vehicles can be deployed automatically in the scenario. NCTUns developers showed interest in Intelligent Transportation Systems (ITS) since version 4.0 when traffic and network simulators were coupled inside a single module to provide a single vehicular environment. With version 4, some important features for ITS simulation were added: a) Driver behaviour model, b) Network road construction, c) RSU and OBU simulation and d) Car agent module.

With its intelligent driving behaviour the car agent can model a car to obey certain parameters like traffic light, nearby vehicle, changing the lane, taking the turn and car following model.

According to Fig. A.1, NCTUns is shown as a complete simulator which comprises both network and traffic simulators.

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