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Improving Vehicular ad hoc Network Protocols to Support Safety Applications in Realistic Scenarios

Thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Computer Science

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To my wife, Piedad,
and my daughter, Sara.

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Abstract

The convergence of telecommunication, computing, wireless, and transportation technologies facilitates that our roads and highways can be both our communications and transportation platforms. These changes will completely revolutionize when and how we access services, communicate, commute, entertain, and navigate, in the coming future. Vehicular ad hoc networks (VANETs) are wireless communication networks that do not require any fixed infrastructure, and support cooperative driving among communicating cars on the road. Vehicles act as communication nodes and relays, forming dynamic vehicular networks together with other near-by vehicles on the road and highways.

The specific characteristics of vehicular networks favor the development of attractive and challenging services and applications. In this thesis we focus on safety applications. Specifically, we develop and evaluate a novel protocol to improve safety on the road. Our proposal combines location information of vehicles, and roadmap scenario characteristics, to improve warning message dissemination. In safety-based applications for vehicular networks our approach is able to reduce the broadcast storm problem while maintaining a high message dissemination effectiveness towards surrounding vehicles.

Since deploying and testing VANETs involves high cost and intensive labor, simulation is a useful alternative prior to actual implementation. However, unlike other previous works, we seek to fully address the peculiarities of vehicular mobility and urban radio transmission, especially when buildings interfere with radio signal propagation. With this purpose, we develop more accurate and realistic VANET simulation tools by improving both the radio propagation and the mobility models, achieving a solution that allows integrating real roadmaps into the simulation framework. Finally, we assess the performance of our proposed protocol using our enhanced simulation platform, evidencing the importance of an adequate simulation framework to achieve more realistic results and draw more meaningful conclusions.

Resumen

La convergencia de las telecomunicaciones, la informática, la tecnología inalámbrica y los sistemas de transporte, va a facilitar que nuestras carreteras y autopistas nos sirvan tanto como plataforma de transporte, como de comunicaciones. Estos cambios van a revolucionar completamente cómo y cuándo vamos a acceder a determinados servicios, comunicarnos, viajar, entretenernos, y navegar, en un futuro muy cercano. Las redes vehiculares ad hoc (*vehicular ad hoc networks VANETs*) son redes de comunicación inalámbricas que no requieren de ningún tipo de infraestructura, y que permiten la comunicación y conducción cooperativa entre los vehículos en la carretera. Los vehículos actúan como nodos de comunicación y transmisores, formando redes dinámicas junto a otros vehículos cercanos en entornos urbanos y autopistas.

Las características especiales de las redes vehiculares favorecen el desarrollo de servicios y aplicaciones atractivas y desafiantes. En esta tesis nos centramos en las aplicaciones relacionadas con la seguridad. Específicamente, desarrollamos y evaluamos un novedoso protocol que mejora la seguridad en las carreteras. Nuestra propuesta combina el uso de información de la localización de los vehículos y las características del mapa del escenario, para mejorar la diseminación de los mensajes de alerta. En las aplicaciones de seguridad para redes vehiculares, nuestra propuesta permite reducir el problema de las tormentas de difusión, mientras que se mantiene una alta efectividad en la diseminación de los mensajes hacia los vehículos cercanos.

Debido a que desplegar y evaluar redes VANET supone un gran coste y una tarea dura, la metodología basada en la simulación se muestra como una metodología alternativa a la implementación real. A diferencia de otros trabajos previos, con el fin de evaluar nuestra propuesta en un entorno realista, en nuestras simulaciones tenemos muy en cuenta tanto la movilidad de los vehículos, como la transmisión de radio en entornos urbanos, especialmente cuando los edificios interfieren en la propagación de la señal de radio. Con este propósito, desarrollamos herramientas para la simulación de VANETs más precisas y realistas, mejorando tanto la modelización de la propagación de radio, como la movilidad de los vehículos, obteniendo una solución que permite integrar mapas reales en el entorno de simulación. Finalmente, evaluamos las prestaciones de nuestro protocolo propuesto haciendo uso de nuestra plataforma de simulación mejorada, evidenciando la importancia del uso de un entorno de simulación adecuado para conseguir resultados más realistas y poder obtener conclusiones más significativas.

Resum

La convergència de les telecomunicacions, la informàtica, la tecnologia sense fil i els sistemes de transport facilitarà ben aviat que les nostres carreteres i autopistes ens servisquen tant com a plataforma de transport com de comunicacions. Aquests canvis revolucionaran completament, en un futur molt proper, com i quan accedim a determinats serveis, ens comuniquem, viatgem, ens entretenim i naveguem. Les xarxes vehiculars ad hoc (vehicular ad hoc networks o VANETs en anglès) són xarxes de comunicació sense fil que no requereixen cap mena d'infraestructura, i que permeten la comunicació i la conducció cooperativa entre els vehicles que hi ha a la carretera. Els vehicles actuen com a nodes de comunicació i transmissors, i formen xarxes dinàmiques junt amb altres vehicles que s'hi troben propers als carrers i les autopistes.

Les característiques especials que presenten les xarxes vehiculars afavoreixen el desenvolupament de serveis i aplicacions atractives i que suposen un veritable repte. En aquesta tesi ens hem centrat en les aplicacions relacionades amb la seguretat. Concretament, hi hem desenvolupat i avaluat un nou protocol que millora la seguretat a les carreteres. La nostra proposta combina l'ús d'informació sobre la localització dels vehicles i sobre les característiques del mapa de l'escenari per tal de millorar la disseminació dels missatges d'alerta. En les aplicacions de seguretat per a xarxes vehiculars, la nostra aproximació permet reduir el problema de les tempestes de difusió, mentre que es manté una alta efectivitat en la disseminació dels missatges cap als vehicles propers.

Atès que desplegar i provar les VANET suposa un gran cost i una tasca ben dura, la simulació es mostra com una tasca alternativa i prioritària a la implementació real. Però, a diferència d'altres treballs previs, nosaltres ens hem proposat tractar les peculiaritats en la mobilitat dels vehicles i de la transmissió de ràdio en entorns urbans, especialment quan els edificis interfereixen la propagació del senyal de ràdio. Amb aquest objectiu hem desenvolupat eines per a la simulació de VANET més precises i realistes, i hem millorat tant la modelització de la propagació de ràdio com la mobilitat dels vehicles, amb la qual cosa hem obtingut una solució que permet integrar mapes reals a l'entorn de simulació. Finalment, hem avaluat les prestacions del protocol que proposem fent ús de la nostra plataforma de simulació millorada, i hem evidenciat la importància de l'ús d'un entorn de simulació adequat per a aconseguir resultats més realistes i poder arribar a conclusions més significatives.

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Chapter 1

Motivation, Objectives and Organization of the Thesis

1.1 Motivation

A massive deployment of devices with wireless capabilities has been prominent during the last decade. Nevertheless, during the next few years, this trend is expected to become even more pronounced. Most of the wireless networks available nowadays are infrastructure-based. However, users may not always want to communicate using an infrastructure due to security, costs, or bandwidth constraints.

In vehicular environments, wireless technologies such as *Dedicated Short Range Communication* (DSRC) [XSMK04] and IEEE 802.11p *Wireless Access for Vehicular Environment* (WAVE) [Tas06] enable peer-to-peer mobile communication among vehicles (V2V) and communication between vehicles and the infrastructure (V2I). V2V communications allow the transmission of small messages to improve traffic safety. V2I communications, in contrast, allow users to access higher level applications usually related to infotainment. We think that the combination of V2V and V2I communications can propel our communication capabilities even further, allowing us to communicate anytime and anywhere, improving the future Intelligent Transportation Systems (ITS) and increasing our life quality tremendously.

The specific characteristics of vehicular networks favor the development of attractive and challenging services and applications. In this thesis we focus on safety applications. Specifically, our aim is to improve traffic safety using vehicular networks. To that end, we will develop a warning message dissemination mechanism for vehicular networks. Our proposal will reduce the broadcast storm problem while maintaining a high message dissemination effectiveness towards surrounding vehicles.

Deploying and testing Vehicular Ad Hoc Networks (VANETs) involves high cost and intensive labor. Hence, simulation is a useful alternative prior to actual implementation. VANET simulations often involve large and heterogeneous scenarios. Compared to Mobile Ad Hoc Networks (MANETs) [MC], the simulation of VANETs must account for some specific characteristics found in vehicular environments. The increasing popularity and attention in VANETs has prompted researchers to develop accurate and realistic simulation tools. In general, they all exhibit good software support. However, they are poor in scalability and complex to use. In fact, current network simulators do not specifically address VANET scenarios and requirements, and thus do not support IEEE 802.11p, obstacles, and vehicular traffic models. Hence, we need to improve the simulation environment making it possible to simulate more realistic VANET scenarios in order to assess our proposals.

1.2 Objectives of the Thesis

In 2007, when the first steps of this thesis were taken, wireless vehicular networks based on the IEEE 802.11 standard and cellular telephony technologies were scarce and limited to a few laboratory testbeds. Although a lot of work related to wireless ad hoc networks had been done, the special characteristics of vehicular environments required more research work in order to solve the specific problems inherent to wireless vehicular networks.

The first objective of this thesis is to propose a system for reducing the Emergency Services Responsiveness. In order to improve the chances of survival for passengers involved in car accidents, it is desirable to reduce the response time of rescue teams and to optimize the medical and rescue resources needed. A faster and more efficient rescue will increase the chances of survival and recovery for injured victims. Thus, once the accident has occurred, it is crucial to efficiently and quickly manage the emergency rescue and resources. In this thesis we want to propose a novel warning dissemination protocol which will improve traffic safety increasing the warning message broadcast effectiveness in vehicular networks by reducing the broadcast storm problem [TNCS02], while maintaining a high message dissemination effectiveness towards surrounding vehicles.

The second objective of this thesis is to make a survey of the different available VANET simulation frameworks, including several publicly available mobility generators, network simulators, and VANET simulators. Although the currently available simulators provide a good simulation environment for VANETs, they do not specifically address VANET scenarios and requirements, such as the consideration of 802.11p, obstacles, or vehicular traffic models, so refinements and further contributions are needed before they can be widely used by the research community.

The third objective is determining the key factors when simulating VANETs. Our purpose is to determine what are the key factors affecting *Warning Message Dissemination* (WMD) in order to concentrate on such parameters, thus reducing the amount of required simulation time when evaluating traffic safety applications for VANETs.

As a fourth objective we want to improve the simulation of VANETs by enhancing both the physical layer and the mobility models, achieving a solution that allows integrating real roadmaps into the simulation framework. We wish to develop an application to generate realistic mobility models to simulate VANETs in urban scenarios. In addition, we want to modify the ns-2 simulator in order to: (i) improve the simulation of the radio propagation process in vehicular environments, and (ii) allow researchers to simulate real maps, making it possible for researchers to get more realistic results in their simulations. Using our future enhanced simulation platform we want evaluate our proposal, i.e. the aforementioned warning dissemination protocol.

After describing our distinct objectives in detail, we proceed by making a joint evaluation of all the previous proposals, obtaining a clear picture of the overall improvements achieved.

1.3 Organization of the Thesis

This thesis is organized as follows: in Chapter 2 we show how vehicular networks can be used in Intelligent Transportation Systems (ITS), emphasizing on how vehicular networks may improve the current emergency services' response to traffic accidents. In Chapter 3 we make an introduction to Vehicular Ad Hoc Networks (VANETs), showing their main characteristics and applications. We also make a background introduction to the different standards that support this kind of network. Additionally, we also present the existing broadcast storm reduction techniques, and we make a review of the previous research work on dissemination of warning messages in VANETs.

Chapter 4 highlights the importance of using simulation to develop preliminary versions of protocols. We refer to some available mobility models for vehicular environments, some existing VANET simulation frameworks, and the existing *Radio Propagation Models* (RPMs) typically used in VANET simulations. In Chapter 5 we determine which are the key factors in VANET simulations. Our purpose is to determine what are the key factors affecting *Warning Message Dissemination* (WMD) in order to concentrate on such parameters, thus reducing the amount of simulation time required when evaluating traffic safety applications for VANETs.

In order to improve VANET simulations, Chapter 6 presents our proposal regarding *VANET Mobility Models*, a concept that must be accounted for when we wish to obtain accurate simulation results. Moreover, in Chapter 7 we propose some novel RPMs specially designed to be used in VANETs.

Chapter 8 is dedicated to efficient dissemination of warning messages in vehicular networks in order to improve traffic safety. We propose the Street Broadcast Reduction (SBR) scheme, a novel algorithm that improves warning message dissemination, and that also mitigates the broadcast storm problem. SBR is particularly useful in cities and road intersections, being a more realistic model to account for obstacles and non line-of-sight scenarios. The SBR scheme outperforms other available schemes in high density urban scenarios, yielding a lower percentage of blind vehicles while drastically alleviating the broadcast storm problem.

Finally, in Chapter 9 we present a summary of the main results of this thesis, along with some concluding remarks. We also include a list of the publications related to the thesis, and we comment on possible future research works that can derive from the work here presented.

Chapter 2

Vehicular Networks

Over the years, we have harnessed the power of computing to improve the speed of operations and increase in productivity. Also, we have witnessed the merging of computing and telecommunications. This excellent combination of two important fields has propelled our capabilities even further, allowing us to communicate anytime and anywhere, improving our work flow and increasing our life quality tremendously.

The next wave of evolution we foresee is the convergence of telecommunications, computing, wireless, and transportation technologies. Once this happens, our roads and highways will be both our communications and transportation platforms, which will completely revolutionize when and how we access services and entertainment, how we communicate, commute, navigate, in the coming future. This chapter presents an overview of the current state-of-the-art, discusses current projects, their goals, and finally highlights how emergency services and road safety will evolve with the blending of vehicular communication networks and road transportation.

2.1 Introduction

The population of the world has been increasing, with China and India being the two most densely populated countries. Road traffic has also been getting more and more congested, as a higher population and increased business activities result in greater demand for cars and vehicles for transportation. While careful city planning can help to alleviate transportation problems, such planning does not usually scale well over time with unexpected growth in population and road usage.

Modernization, migration, and globalization have also taken great tolls on road usage. Inadequacy in transportation infrastructures can cripple a nation's progress, social well-being, and economy. It can also make a country less appealing to foreign investors and can cause more pollution as vehicles spend a longer time waiting on congested roads. Increased delays can also result in road rage, which gives rise to more social problems, which are undesirable. With fuel price soaring and potential threats of fuel shortage, we are now faced with greater challenges in the field of transportation systems. In addition to this trend, technology has also impacted transportation, giving it a different outlook.

In the past, people were focused on how to build efficient highways and roads. Over time, focus shifted to mechanical and automotive engineering, in the pursuit of building faster cars to surmount greater distances. Later on, electronics technology impacted the construction of cars, embedding them with sensors and advanced electronics, making cars more intelligent, sensitive and safe to drive on. Now, innovations made so far in wireless mobile communications and networking technologies are starting to impact cars, roads, and highways. This impact will drastically change the way we view transportation systems of the next generation and the way we drive in the future. It will create major economic, social, and global impact through a transformation taking place over the next 10-15 years. Hence, technologies in the various fields have now found common grounds in the broad spectrum of the Next Generation Intelligent Transportation Systems (ITS).

In this chapter we examine the impact of future ITS technologies on road safety and emergency services. This chapter is organized as follows: Section 2.2 introduces the current advances and world trends regarding road safety, vehicular communication networks, and telematics. Section 2.3 presents the motivation of using wireless networks in vehicular environments. Section 2.4 discusses the problems related to road safety and the emergency services. The evolution of communications in emergency services when an accident occurs is described in Section 2.5. Section 2.6 presents the different issues regarding ITS and vehicular communications that we envision. Finally, Section 2.7 concludes this chapter.

2.2 Advances and Trends in Vehicular Network Technologies

Recently, there have been several projects and research efforts conducted globally to address road safety, vehicular communication networks, and telematics.

IN KOREA - The Korean Telematics Business Association was established in 2003 with the aim of boosting the telematics industry and to standardize telematic technologies and services. Its members are primarily automakers, telecommunication companies, terminal manufacturers, and content providers. Its core functions include: (a) coordinating Korean government projects related to telematics, (b) market promotion, (c) standardization efforts, and (d) international collaboration in conferences, road shows, etc.

IN JAPAN - The topics on ITS have been actively addressed by Japanese researchers and Japanese government agencies over the years. Specifically, the Japanese Ministry of Land, Infrastructure and Transport (MLIT) is the bureau of the Japanese government that decides on policies in ITS. In Japan, ITS are viewed as a new transport system that comprises an advanced information and telecommunications network for users, roads, and vehicles. Specifically, nine developments areas have been identified: (a) navigation systems, (b) electronic toll collection (ETC) systems, (c) assistance for safe driving, (d) optimization of traffic

Table 2.1: ITS projects in Japan

Japan ITS Funded Projects	**Remarks**
AHS [mli03]	**Advanced Cruise-Assist Highway Systems** It aims at reducing traffic accidents, enhancing safety, improving transportation efficiency, as well as reducing the operational work of drivers. AHS research is being carried out in the following fields: - AHS-"i" (information) focusing on providing information. - AHS-"c" (control): vehicle control assistance. - AHS-"a" (automated cruise): fully automated driving. Its applications include obstacle detection and avoidance, speed control, driving control and man-machine interfaces.
ASV [mli03]	**Advanced Safety Vehicle** It was launched in order to transfer advanced technologies to vehicles for their greater safety. In the second phase, the extent of research has been expanded to include trucks, buses and motorcycles. Automated driving technology and basic vehicular technology areas have been added to the major safety technology field. Also, research and development will be promoted in connection with infrastructures, using two systems: autonomous type and infrastructure-employed type. This will make it possible to combine ASV with AHS.

management, (e) efficiency in road management, (f) support for public transport, (g) efficiency in commercial vehicles, (h) support for pedestrians, and (i) support for emergency vehicle operations. Table 2.1 shows the most important ITS projects funded by the Japanese MLIT. Both projects aim to enhance safety and reduce traffic accidents while improving transportation efficiency.

IN THE USA - There are two major programs sponsored by the US DoT (Department of Transportation). The first one is the Vehicle Safety Communication (VSC) project. The second one is related to Vehicle Infrastructure Integration (VII). A VII consortium has been formed to engage key industrial players, state and local governments, as well as other partners to work on an information infrastructure for real-time communications between vehicles. The motivations for a VII program in the USA are well justified. American roadways indeed have a safety and congestion problem. In fact, in 2006, there were 6 million traffic crashes in the USA alone, injuring about 2.6 million people. Also, it was observed that a crash occurred every 5 seconds, with someone sustaining a traffic-related injury every 12 seconds. Worse, someone died in a traffic crash every 12 minutes. This death toll is major and astonishing. In addition, road congestion problems have resulted in 4.2 billion hours of travel delay, 2.9 billion gallons of gasoline fuel wasted, and a net urban congestion cost of about $80 billion (according to a 2007 report by the Texas Transportation Institute). Table 2.2 shows the most important USA ITS projects.

Table 2.2: ITS projects in the USA

USA ITS Funded Projects	**Remarks**
VSC [vsc09]	**Vehicle Safety Communication** The main objectives of the VSC project are: - Estimate the potential safety benefits of vehicle safety applications. Define preliminary communications requirements for the high-priority vehicle safety applications. - Evaluate proposed DSRC standards, identify specific technical issues, present vehicle safety requirements, and secure DSRC for safety applications at real intersections. - Identify channel capacity in stressing traffic environments as a large scale deployment issue, determining that the 5.9 GHz DSRC wireless technology is potentially best able to support the communications requirements.
VII [vii09]	**Vehicle Infrastructure Integration** VII will enable safety, mobility, and commercial vehicular services and applications. It will exploit innovations in wireless communications and networking technologies, along with sensing and advanced user interfaces. When deployed, the VII network will allow drivers and travelers to access traffic conditions and routing information, receive warnings about existing or upcoming hazards, and conduct wireless commercial transactions while on-the-move.

IN EUROPE - There are a lot of integrated projects funded by the European Commission under the EU IST 6th Framework (FP6) (2002-2006), and the EU 7th Framework (FP7) extends the program further till 2013. The White Paper on EU Transport Policy for 2010 states a key objective, i.e., 50% reduction of casualties due to road accidents by the end of 2010. Improvements on road safety are achievable by increasing the EU market penetration of Advanced Driver Assistance Systems (ADAS), currently limited by the performance and cost of sensor technologies. This is the prime focus of the European ITS research program. Tables 2.3, 2.4, 2.5, and 2.6 describe some of the most relevant ITS projects funded by the European Union. These projects cover a wide spectrum of research areas, including driver-vehicle interfaces, emergency rescue, preventive road safety, on-board sensors, pedestrian detection, intersection safety, cooperative systems and cooperative networks, maps and geographical technologies, and vehicle-to-vehicle (V2V) communications. In this chapter, we focus on how vehicular communication networks have impacted road safety, and how emergency services will evolve in the future.

2.3 Vehicular Networks: Rationale & Motivation

In the past, the automotive industry built powerful and safer cars by embedding advanced materials and sensors. With the advent of wireless communication technologies, cars are being equipped with wireless communication devices, enabling them to communicate with other cars. Such communications are not plainly restricted to data transfers (such as emails, etc.), but also create new opportunities for enhancing road safety. Some applications only require communication among vehicles, while other applications require the coordination between vehicles and the road-side infrastructure.

The applications and advantages of using vehicular communication networks for enhancing road safety and driving efficiency are diverse, which explains why research in this area has recently emerged. Vehicular communications, however, need the support of reliable link and channel access protocols. The IEEE 802.11p wireless access in vehicular environments (WAVE) [Tas06] is a standardization effort that provides a protocol suite to support vehicular communications in the 5.9 GHz licensed frequency band (5.85-5.925 GHz).

WAVE supports both vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. Also, WAVE can enhance road safety and driving efficiency since it offers the required support to provide faster rescue operations, generate localized warnings of potential danger, and convey real-time accident warnings. WAVE complements satellite, WiMax, 3G, and other communications protocols by providing high data transfer rates (3-54 Mbps) in circumstances where the latency in the communication link is too high, and where isolating relatively small communication zones is important. Details about radio frequencies, modulation, link control protocols and media access can be found in [UDSAM09].

Concerning safety using vehicular networks, in [Toh07], cars can act as communication relays (routers) to form ad hoc vehicular networks via wireless communication links. Cars are restricted by the physical boundaries of the road and

Table 2.3: ITS projects in EU

EU ITS Funded Projects	**Remarks**
AIDE [aid09b]	**Adaptive Integrated Driver-vehicle Interface** The general objective is to generate knowledge and develop methodologies and human-machine interface technologies required for safe and efficient integration of ADAS (Advanced Driver Assist Systems), IVIS (In-Vehicle Information Systems) and nomad devices into the driving environment. The aims of AIDE are: - to maximize the efficiency, and hence the safety benefits, of advanced driver assistance systems - to minimize the level of workload and distraction imposed by in-vehicle information systems and nomad devices - to enable the potential benefits of new in-vehicle technologies and nomad devices in terms of mobility and comfort
AIDER [aid09a]	**Accident Information and Driver Emergency Rescue** The AIDER project's main objective is the reduction of road accident consequences by optimizing the rescue management in terms of operative time and effectiveness. AIDER vehicles will be equipped with a detection system to monitor the on-board pre- and post-crash environment. The project envisaged a kind of automotive "black box", which would continually assess a car's environment, including speed, terrain and many other factors. Should there be an accident, the box would perform a quick calculation, comparing the state of the vehicle before and after impact. This would yield important information about where the car was hit, how quickly the car stopped, and therefore how severe the accident was. The box would then alert a call center with essential details about the nature of the crash, which could be reconstructed. Since the emergency services would be contacted immediately and provided with details about the accident, they would arrive more quickly and be better prepared for specific injuries.
ATLANTIC [atl09]	**A Thematic Long-term Approach to Networking for the Telematics & ITS Community** The ATLANTIC Thematic network will operate as an Electronic Forum organized and coordinated through three geographically based network coordinators, one for each of Europe, Canada and USA. The ATLANTIC project has three parts: (1) Operation of an ITS Forum based on e-mail groups, involving key individuals in the field of Transport Telematics and Intelligent Transport Systems (ITS). The Forum sub-groups will be benchmarking the coverage, content and results of the European ITS programs against similar activities in the USA and Canada. (2) International meetings with American and Canadian partners in the project, which are self-funded. (3) Development of good practice and policy on telematics-based travel information services for cities and regions.

Table 2.4: ITS projects in EU (Cont.)

EU ITS Funded Projects	**Remarks**
PREVENT [pre09]	**Preventive and Active Safety Applications Contribute to the Road Safety Goals on European Roads** In PReVENT, a number of subprojects are proposed within clearly complementary function fields: Safe Speed and Safe Following, Lateral Support and Driver Monitoring, Intersection Safety, and Vulnerable Road Users and Collision Mitigation. The goal of Integrated Project PReVENT is to contribute to the: - Road safety goal of 50% fewer accidents by 2010 - as specified in the key action eSafety for Road and Air Transport from the European Union. - Competitiveness of the European automotive industry. - European scientific knowledge community on road transport safety. - Congregation and cooperation of European and national organizations and their road transport safety initiatives.
ADOSE [ado09]	**Reliable Application Specific Detection of Road Users with Vehicle On-board Sensors** ADOSE addresses research challenges in the area of "accident prevention through improved-sensing including sensor fusion and sensor networks". Focus is also on "increased performance, reliable and secure operation" for "new generation advanced driver assistance systems". The project is focused mainly on sensing elements and their pre-processing hardware, as a complementary project to PReVENT. Novel concepts and sensory systems will be developed based on Far Infrared cameras, CMOS vision sensors, 3D packaging technologies, ranging techniques, bio-inspired silicon retina sensors, harmonic microwave radar and tags.
INTERSAFE-2 [int09]	**Cooperative Intersection Safety** The INTERSAFE-2 project aims to develop and demonstrate a Cooperative Intersection Safety System (CISS) that is able to significantly reduce injury and fatal accidents at intersections. The novel CISS combines warning and intervention functions based on novel cooperative scenario interpretation and risk assessment algorithms. The cooperative sensor data fusion is based on advanced on-board sensors for object recognition, a standard navigation map, and information supplied over a communications link from other road users via V2V and infrastructure sensors and traffic lights via V2I.
SAFERIDER [saf09a]	**Advanced Telematics for Enhancing the Safety and Comfort of Motorcycle Riders** SAFERIDER aims to study the potential of ADAS/IVIS integration on motorcycles for the most crucial functionalities, and develop efficient and rider-friendly interfaces and interaction elements for riders' comfort and safety. SAFERIDER aims to enhance riders' safety by introducing four ADAS applications: (a) speed alert, (b) curve speed warning, (c) frontal collision warning, and (d) intersection support.

Table 2.5: ITS projects in EU (Cont.)

EU ITS Funded Projects	**Remarks**
SafeSpot [saf09b]	**Cooperative vehicles and road infrastructure for road safety** The objective of the project is to understand how intelligent vehicles and intelligent roads can cooperate to increase road safety. SafeSpot seeks to: - Use the infrastructure and the vehicles as sources and destinations of safety-related information and develop an open, flexible and modular architecture and communications platform. - Develop the key enabling technologies: ad-hoc dynamic network, accurate relative localization, dynamic local traffic maps. - Develop and test scenario-based applications to evaluate the impacts on road safety. - Define a sustainable deployment strategy for cooperative systems for road safety, evaluating also related liability, regulations and standardization aspects.
I-WAY [iwa09]	**Intelligent Cooperative Systems in Car for Road Safety** The goal of I-WAY is to develop a multi-sensorial system that can ubiquitously monitor and recognize the psychological condition of drivers as well as special conditions prevailing in the road environment. The I-WAY platform targets mainly road users, but it is a highly modular system that can be easily adapted or break up in standalone modules in order to accommodate a wide variety of applications and services in several fields of transport, thanks to its interoperability and scalable system architecture. The I-Way project is strongly committed to achieve the two strategic objectives of (a) increasing road safety, and (b) bettering transport efficiency.
COMeSafety [com09]	**Communications for eSafety** The COMeSafety Project supports the eSafety Forum with respect to all issues related to V2V and V2I communications as the basis for cooperative intelligent road transport systems. COMeSafety provides an open and integrating platform, aiming at representing the interests of all public and private stakeholders. COMeSafety acts as a broker for the consolidation and following standardization of research project results, work of the C2C-CC and the eSafety Forum. Its aims are: - Coordination and consolidation of research results and their implementation. - eSafety Forum support in case of Standardization and Frequency Allocation. - Worldwide harmonization (Japan/US/Europe). - Support the frequency allocation process. - Dissemination of the results.

Table 2.6: ITS projects in EU (Cont.)

EU ITS Funded Projects	**Remarks**
HIGHWAY [hig09]	**Breakthrough Intelligent Maps and Geographic Tools for the context-aware-delivery of E-safety and added value services** HIGHWAY combines smart real-time maps, UMTS 3G mobile technology, positioning systems and intelligent agent technology, 2D/3D spatial tools, and speech synthesis/voice recognition interfaces to provide European car drivers and pedestrians with eSafety services and interaction with multimedia (text, audio, images, real-time video, voice/graphics) and value-added-location-based services. HIGHWAY maps will help drivers facing critical driving situations.
CarTALK2000 [car09]	**Advanced driver support system based on V2V communication technologies** CarTALK2000 was established within the EU's ADASE2 (Advanced Driver Assistance Systems Europe) ITS project. Its main objectives were the development of cooperative driver assistance systems and a self-organizing ad hoc radio network as the basis for communication with the aim of preparing a future standard. It incorporated three applications: a warning system that relays information about accidents ahead, break-downs and congestion; a longitudinal control system; and a cooperative driving assistance system that supports merging and weaving.
COOPERS [coo09]	**Cooperative Networks for Intelligent Road Safety** COOPERS focuses on the development of innovative telematic applications on the road infrastructure with the long term goal of a Cooperative Traffic Management between vehicle and infrastructure, thus reducing the self opening gap on telematic application development between car industry and infrastructure operators. The goal of the project is the enhancement of road safety by direct and up-to-date traffic information based on wireless communication between infrastructure and motorized vehicles on a motorway section.
CVIS [cvi09]	**Cooperative Vehicle-Infrastructure Systems** Contrarily to SafeSpot, this European project focuses on vehicle-to-infrastructure communications alone. The goals set are: - To create a unified technical solution allowing all vehicles and infrastructure elements to communicate with each other in a continuous and transparent way using a variety of media with enhanced localization. - To define and validate an open architecture and system concept for a number of cooperative system applications, and develop common core components to support cooperation models in real-life applications and services for drivers, operators, industry and other key stakeholders. - To address issues such as user acceptance, data privacy and security, system openness and interoperability, risk and liability, public policy needs, cost/benefit and business models, and roll-out plans for implementation.

highways. For example, cars on one lane all travel in the same direction, keeping ample safe distance from one to another. The ability of neighboring cars to communicate wirelessly allows them to warn each other about any abnormalities or potential dangers. This, in contrast to the old way of "signaling" using visual lights, is far superior, especially when visibility is poor due to bad weather conditions. Another scenario is the ability of cars to convey accident information to other neighboring cars via V2V communications so that they can slow down and be aware of the potential danger ahead. Also, in times of road congestion, V2V communications can allow other cars further down the road to make plans to exit the highway or to seek alternate routes to their destinations, hence avoiding further congestions.

V2V communications have the following advantages: (i) allow short and medium range communications, (ii) present lower deployment costs, (iii) support short messages delivery, and (iv) minimize latency in the communication link. Nevertheless, V2V communications present the following shortcomings: (i) frequent topology partitioning due to high mobility, (ii) problems in long range communications, (iii) problems using traditional routing protocols, and (iv) broadcast storm problems [TNCS02] in high density scenarios.

Currently, there are several projects that address V2V communication issues. Wisitpongphan et al. [WTP$^+$07] quantified the impact of broadcast storms in VANETs in terms of message delay and packet loss rate, in addition to conventional metrics such as message reachability and overhead. They proposed three probabilistic and timer-based broadcast suppression techniques: (i) the weighted p-persistence, (ii) the slotted 1-persistence, and (iii) the slotted p-persistence scheme. The authors also studied the routing problem in sparse VANETs [WBM$^+$07]. In [TWB07], they proposed a new Distributed Vehicular Broadcasting protocol (DV-CAST) to support safety and transport efficiency applications in VANETs. Results showed that broadcasting in VANET is very different from routing in mobile ad hoc networks (MANET) due to several reasons such as network topology, mobility patterns, demographics, and traffic patterns at different times of the day. These differences imply that conventional ad hoc routing protocols will not be appropriate in VANETs for most vehicular broadcast applications. The designed protocol addressed how to deal with extreme situations such as dense traffic conditions during rush hours, sparse traffic during certain hours of the day (e.g., midnight to 4 am in the morning), and low market penetration rate of cars using DSRC technology. Table 2.7 shows some of the major testbeds related to ITS/VANET developed by National Labs and Universities that have been used to test and evaluate vehicular network solutions.

Concerning V2I, current research efforts include: (a) information dissemination for VANETs, especially using advanced antennas [KRS$^+$07], (b) VANET/Cellular interoperability [SRS$^+$08], and (c) WiMAX penetration in vehicular scenarios [YOCH07]. The integration of Worldwide Interoperability for Microwave Access (WiMAX) and Wireless fidelity (WiFi) technologies seems to be a feasible option for better and cheaper wireless coverage extension in vehicular networks. WiFi, under the 802.11p standard, is a good candidate to be used in V2V communications. Its weakness is short coverage. WiMAX multi-hop relay networks that

Table 2.7: ITS/VANET testbeds developed by National labs and Universities

Institution	**Remarks**
Carnegie Mellon University [cmu09]	The GM Collaborative Research Lab at Carnegie Mellon University developed the Smart Car testbed, which allows the car to recognize the driver's settings and keep him alert. It has the following features: - "Context aware", i.e. it responds to driver's needs and preferences, road and weather conditions, and information from the Internet based on demand. - It is also equipped with a "gesture interface" that allows drivers to control the car's electronics with a wave of their hand. - Built with a speech recognition system tuned to the driver's voice that connects the car to handheld computers and cell phones. - Assembled with a heads-up display for operating the radio, navigating, checking email, and the driver's schedule.
German Consortium [sim09]	A Consortium formed by automotive and telecommunication companies, the state government, and German universities is collaborating in the simTD initiative which tries to put the results of previous research projects into practice. The overall simTD test fleet comprises an internal fleet with up to 100 controlled test vehicles as well as an external fleet with approximately 300 vehicles. The internal simTD fleet of test vehicles comprises 20 core vehicles with expert drivers. 80 further vehicles are driven by persons without special training. The expert drivers will be asked to work together locally and on their own initiative to create certain scenarios. The other drivers' reaction to the respective scenario can then be used to evaluate its efficiency, safety, and acceptability of functions.
Rutgers University [rut09]	The DisCo Lab developed TrafficView, which defines a framework to disseminate and gather information about the vehicles on the road. With such a system, a vehicle's driver will be provided with road traffic information that helps driving in situations such as foggy weather, or finding an optimal route in a trip several miles long. The demonstration of the TrafficView system was performed with four vehicles, which continuously exchanged speed and location information over wireless networking technology, as they navigated across the Rutgers University campus.
Berkeley [pat09]	The California Partners for Advanced Transit and Highways (PATH) and the Department of Transportation (Caltrans) in partnership with public agencies and private industry are working in vehicle-to vehicle and vehicle-to-roadside communications on their IntelliDrive (formerly Vehicle-Infrastructure Integration, VII) testbed. IntelliDrive is a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices.

employ relay stations could extend coverage and reduce the cost of deploying a vehicular infrastructure in the near future. With the emergence of new applications (Internet access, infotainment, social networking, etc.), the use of fixed infrastructure will become an attractive option [WTP$^+$07].

A prerequisite for the successful deployment of vehicular communications is to make the system secure. It is essential, for example, to make sure that critical information cannot be modified by any attacker (hacker). Recently, there has been some work dealing with security for VANETs. In [RH05], the authors provided a detailed threat analysis and devised an appropriate security architecture. They also provided a set of security protocols, and analyzed their robustness. In [CPHL07], the authors showed how to achieve efficient and robust pseudonym-based authentication. They presented mechanisms that reduce the security overhead for safety beaconing, and retain robustness for transportation safety, even in adverse network settings. Their proposal enabled vehicle on-board units to generate their own pseudonyms, without affecting the system security. In [YOW09], the authors suggested a method of using on-board radar to detect neighboring vehicles and to confirm their announced coordinates. They addressed position security and ways to counteract Sybil attacks.

In this thesis we focus on traffic safety applications, in order to reduce the number of accidents. Specifically, we improve the warning message broadcast effectiveness in safety applications for vehicular networks.

2.4 Road Safety and Emergency Services

Driver safety involves several factors such as understanding road conditions, having an appropriate response time towards emergencies, crash prevention procedures, etc. Overall, it is accepted that increased road safety can be achieved by exchanging relevant safety information via V2V and V2I communications, where alert information is either presented to the driver or used to trigger active safety systems (such as air bags and emergency brakes). Some of these applications will only be possible if the penetration rate of VANET-enabled cars is high enough.

A collision warning system on a vehicle needs to know the trajectories of neighboring vehicles and the configuration of the neighboring roadway. Most collision warning systems in the literature learn about the state of the neighborhood by using sensors like radar or laser vision systems.

In contrast, modern Cooperative Collision Warning (CCW) systems will construct their knowledge of the neighborhood by listening to the wireless transmissions of other vehicles. This has the advantage of a potentially inexpensive complement of on-board vehicle equipment (compared to ranging sensors, that could provide 360-degree coverage), as well as providing information from vehicles that may be occluded from direct line-of-sight of the approaching vehicle [SRS$^+$07].

Examples of CCW applications are: (a) Forward Collision Warning (FCW), where a host vehicle uses messages from the immediate forward vehicle in the same lane to avoid forward collisions, (b) Lane Change Assistance (LCA), where a host vehicle uses messages from the adjacent vehicle in a neighboring lane to assess unsafe lane changes, and (c) Electronic Emergency Brake Light (EEBL), where

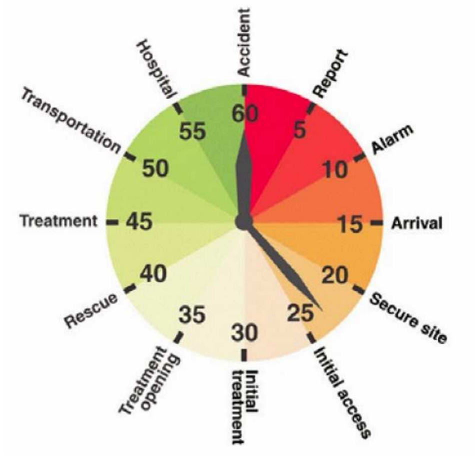


Figure 2.1: Golden hour in a car accident.

a host vehicle uses messages to determine if one, or more, leading vehicles in the same lane are braking.

Cooperative Driving allows drivers to share information about traffic in order to reduce the incidence of traffic jams, minimize CO2 emissions and prevent accidents on the road. It could also help authorities by providing information about vehicles, their location, and road conditions.

2.4.1 Hazards / Accident Contributing Factors

Road hazards can involve drivers, passengers, and pedestrians on the road. On residential roads, pedestrians are vulnerable as they walk along the sides of the road. At intersections, drivers, passengers, and pedestrians are vulnerable to accidents and collisions. At sharp blends and angles, cars can lose sight of other cars coming from opposite lanes, resulting in unexpected front-end collisions. Poor environmental conditions such as bad weather can also cause accidents. Under situations of heavy rain and fog, poor visibility is the prime factor contributing to car accidents. Slippery roads can also cause cars to skid and result in accidents. Other factors such as natural disasters (e.g. earthquakes) can also result in accidents. Notice that not all environment-based accidents can be rectified or improved.

Another cause for accidents is the driver himself. Drivers who are criminals on-the-run frequently drive at high speeds to avoid police chase. They ignore other on-going vehicles and, at times, even drive in the opposite direction. Such accidents are usually catastrophic. Reckless drivers are those who are usually careless. They change lane without signaling or observing the presence of neighboring cars, resulting in accidents. Fatigued drivers are those who have exhausted themselves physically and hence become less alert while driving. They, too, contribute to accidents due to their slow response to changing road conditions.

The golden hour after a car crash is illustrated by Figure 2.1. It is the time within which medical or surgical intervention by a specialized trauma team has the greatest chance of saving lives. If more than 60 minutes have elapsed by the time the patient reaches the operating table, the chances of survival fall sharply. As shown, typical arrival of medical help takes about 15 minutes. Initial access and treatment only start 25 minutes later. Transportation of the injured to the hospital only takes place 50 minutes later. Hence, time is critical to the survival of the injured in a severe incident. Often, hurdles get in the way of doctors and paramedics, dramatically slowing down the time it takes to get to a patient. Hence, any technologies capable of improving the golden hour will help to save lives.

When an accident occurs, crash detection systems can increase the protection of vehicle occupants by detecting and recognizing the type and severity of the crash, adapting protection systems to the body features and seating positions of passengers depending on the type and seriousness of the impact. Deployment of protective devices must be made in less than 5 milliseconds. Collision impact can be: (a) front impact - where front airbags are deployed and seat-belt tensioners are triggered as early as possible in co-ordination with the airbag concerned, (b) side impact - where thorax and head bags are deployed, (c) rear impact - where seat-belt tensioners are triggered even at low speeds to prevent whiplash injuries, and (d) rollover - where the rollover bar, seat-belt tensioners, and side and head airbags are triggered.

Generally, crash detection systems (CDS) can be divided into pre-crash and post-crash systems. A pre-crash system is a passive automobile safety system designed to reduce the damage caused by a collision. Most CDS use radar, and sometimes laser sensors or cameras to detect an imminent crash. Depending on the system, they may warn the driver, precharge the brakes, retract the seat belts (removing excess slack) and automatically apply partial or full braking to minimize the crash. Other experimental systems allow the vehicle to strengthen its frame just before a side-on collision [cra09], or to stop automatically before an impact [vol09]. Tables 2.8, 2.9, and 2.10 show some pre-crash systems developed by car manufacturers.

Post-crash survivability devices and systems help to minimize the chances of crash injuries or fatalities due to the secondary effects of collision, such as fire. Examples of such devices include: (a) vehicle fuel safety and isolation, (b) fire-resistant materials for vehicle interior, and (c) on-board Black-box based systems (also known as Event Data Recorder, EDR). The Black-box technology allows Automatic Crash Notification, and so it is closely related to crash notification systems such as OnStar [ons09] or eCall [Eur08]. In such systems, cars must be equipped with a kind of black-box that automatically detects the accident when it occurs, records data obtained by in-car sensors, and sends them to the next Public Safety Answering Point (PSAP), in order to ask for help. These systems can also be used to determine the cause of the accident or to inform insurance companies. Modern black-box systems also include a built-in camera to make all the recorded information more precise and intuitive. Moreover, most systems record video for a few seconds just before and after a crash.

The National Highway Traffic Safety Administration (NHTSA) estimates that 85% of new cars will have an EDR (black box system) by 2010 [nth09].

Table 2.8: Pre-Crash developed systems by car automakers

Brand	**Remarks**
Audi	Audi has developed a system called "Pre-Sense Plus", which works in four phases. In the first phase, the system provides warning of an imminent accident, while the hazard warning lights are activated, the side windows and sunroof are closed and the front seat belts are tensioned. In the second phase, the warning is followed by light braking but strong enough to win the driver's attention. The third phase initiates autonomous partial braking at a rate of 3 m/s^2. The fourth phase decelerates the car at 5 m/s^2 followed by automatic deceleration at full braking power, roughly half a second before the projected impact. A second system called "Pre-Sense Rear" is designed to reduce the consequences of rear end collisions. Sunroof and windows are closed, seat belts are tightened in preparation for impact. The system uses radar technology and will be introduced on the 2011 Audi A8.
Ford	Collision Warning with Brake Support was introduced in 2009 on the Lincoln MKS and MKT and the Ford Taurus. This system provides a warning through a Head Up Display (HUD) that visually resembles brake lamps. If the driver does not react, the system pre-charges the brakes and increases the brake assist sensitivity to maximize driver braking performance.
GM	At the end of 2005, GM announced a collision warning system which was based on vehicle-to-vehicle wireless communications. Speeds, direction, and location data, enabled the system to evaluate the level of warnings according to the information it had collected. The system is called "Sixth Sense", and it provides the information at hand and can give the driver a clear warning of another vehicle on the freeway that is either slowing down ahead or pulling across from the side. The system uses a clever mix of GPS receivers and LAN networks, and establishes communication with other vehicles within a few hundred meters.
Honda	- Collision Mitigation Brake System introduced in 2003 on the Inspire uses a radar-based system to monitor the situation ahead and provide automatic braking if the driver does not react to a warning in the instrument panel, along with a tightening of the seat belts. This was the first system to provide automatic braking. - In late-2004 Honda developed an Intelligent Night Vision System which highlights pedestrians in front of the vehicle by alerting the driver with an audible chime and visually displaying them via a HUD.

Table 2.9: Pre-Crash developed systems by car automakers (Cont.)

Brand	**Remarks**
Mercedes-Benz	- Pre-Safe system was unveiled in the fall of 2002 at the Paris Motor Show. Using Electronic Stability Programme (ESP) sensors to measure steering angle, vehicle yaw and lateral acceleration, and Brake Assist sensors to detect emergency braking, Pre-Safe can tighten seat belts, adjust seat positions and close the sunroof if it detects possible collision (including rollover). - Pre-Safe Brake introduced in the fall of 2005 co-operating with simultaneously introduced Brake Assist Plus and Distronic Plus systems provide all the functions of previous Pre-Safe system while adding a radar-based system which monitors the traffic situation ahead and provides automatic partial braking (40% or up to 0.4g deceleration) if the driver does not react to the Brake Assist Plus warnings. - In 2009, Mercedes unveiled Attention Assist which based on 70 parameters attempts to detect the driver's level of drowsiness based on the driver's driving style. This system does not actually monitor the driver's eyes. - Also, in 2009, Mercedes added a fully autonomous braking feature that will provide maximum braking at approximately 0.6 seconds before impact.
Nissan	Nissan is reportedly developing a new "magic bumper" system which raises the accelerator pedal if it senses an impending collision. Once the driver lifts off the pedal, the system then automatically applies the brakes. Infiniti offers a laser-based system for the US market that pre-pressurizes the braking system so maximum force can be applied early.
Volkswagen	The 2011 VW Touareg will incorporate the innovative "Area View" which uses four cameras to detect the Touareg's surroundings and this enhances safety. Moreover, the lane assist function ensures that the vehicle does not stray from the right path; meanwhile, the side assist function warns the driver of vehicles approaching from the rear when changing lanes. Adaptive Cruise Control (ACC) with integrated Front Assist can bring the car to a stop in an emergency and can further tighten seat belts as a precautionary measure.

Table 2.10: Pre-Crash developed systems by car automakers (Cont.)

Brand	**Remarks**
Toyota	- Pre-Collision System is the very first radar-based pre-crash system which uses a forward facing millimeter-wave radar system. When the system determines a frontal collision is unavoidable, it preemptively tightens the seat belts removing any slack and pre-charges the brakes. The advanced Pre-Collision System added a twin-lens stereo camera located on the windshield and a more sensitive radar to detect for the first time smaller "soft" objects such as animals and pedestrians. A near-infrared projector located in the headlights allows the system to work at night. - In 2007, the world's first Driver Monitoring System was introduced on the Lexus LS, using a CCD camera on the steering column; this system monitors the driver's face to determine where the driver is looking at. If the driver's head turns away from the road and a frontal obstacle is detected, the system will alert the driver using a buzzer and if necessary pre-charge the brakes and tighten the safety belts. - In 2008, the Toyota Crown monitors the driver's eyes to detect the driver's level of wakefulness. This system is designed to work even if the driver is wearing sunglasses. Toyota added a pedestrian detection feature which highlights pedestrians and presents them on an LCD display located in front of the driver. The latest Crown also uses a GPS-navigation linked brake assist function. The system is designed to determine if the driver is late in decelerating at an approaching stop sign, it will then sound an alert and can also precharge the brakes to provide optimum braking force if deemed necessary. This system works in certain Japanese cities and requires Japan specific road markings which are detected by a camera. - In March 2009 the redesigned Crown Majesta, further advanced the Pre-Collision System by adding a front-side millimeter-wave radar to detect potential side collisions primarily at intersections and when another vehicle crosses the center line. The latest version slides the rear seat upward, thus placing the passenger in a more ideal crash position if it detects a front or rear impact.
Volvo	- Volvo's Collision Warning with Brake Support was introduced on the 2006 Volvo S80. This system provides a warning through a Head Up Display that visually resembles brake lamps. If the driver does not react, the system pre-charges the brakes and increases the brake assist sensitivity to maximize driver braking performance. - Collision Warning with Brake Assist was introduced on the 2007 Volvo S80, V70 and XC70. The system provides the same function as Collision Warning with Brake Support, but in addition, provides autonomously partial braking if the driver does not react to the brake assist functions.

2.5 Trends in Emergency Services: From Cellular to VANET-based

The demand for emergency road services has risen around the world. Moreover, changes in the role of emergency crews have occurred - from essentially transporting injured persons (to the hospital) to delivering basic treatment or even advanced life support to patients before they arrive at the hospital. In addition, advances in science and technologies are changing the way emergency rescue operates.

In times of road emergency, appropriately skilled staffs and ambulances should be dispatched to the scene without delay. Efficient roadside emergency services demand the knowledge of accurate information about the patient (adult, child, etc), their conditions (bleeding, conscious or unconscious, etc), and clinical needs. In order to improve the chances of survival for passengers involved in car accidents, it is desirable to reduce the response time of rescue teams and to optimize the medical and rescue resources needed. A faster and more efficient rescue will increase the chances of survival and recovery for injured victims. Thus, once the accident has occurred, it is crucial to efficiently and quickly manage the emergency rescue and resources.

An Automatic Crash Notification system will automatically notify the nearest emergency call center when a vehicle crashes. These call centers will determine the nature of the call and, if it is an emergency, data from vehicular sensors will allow the call center to evaluate if the vehicle has been involved in a collision. Vehicular sensors may indicate that an airbag was triggered, the mechanical impact on the vehicle, whether the vehicle did roll-over, the deceleration history and status, the number of passengers in the car, etc. Knowing the severity of emergencies and their precise locations can save lives readily while utilizing rescue resources efficiently.

The method for seeking help when an accident occurs has changed over the years. Figure 2.2 shows the old method of accident notification, where a witness of the car accident calls the police for help. Basically, the witness gives information about the location of the accident and the fatalities involved. Once the police is notified, they coordinate the rescue effort by alerting the fire department and medical services, summoning for an ambulance to the accident site quickly.

Figure 2.3 shows the current method of accident notification. When an accident occurs, a call is made to an "answering point" in order to send information about the accident and to ask for help.

eCall [ece02] is one of the most important road safety efforts made under the European Union's eSafety initiative. eSafety seeks to improve road safety by fitting intelligent safety systems based on advanced electronic technologies into road vehicles. In the event of an emergency, the single European emergency number 112 can be called from all the European Union countries.

eCalls are made free of charge from fixed-line or mobile phones. eCall builds on E112 [Eur08], a location-enhanced version of 112. The telecom operator transmits the location information to the Public Safety Answering Point (PSAP), which in return must be adequately equipped with a voice-band modem detector, Minimum Set of Data (MSD) decoding capabilities, and trained operators to process this data. PSAP and emergency service chains must be capable of dealing with calls

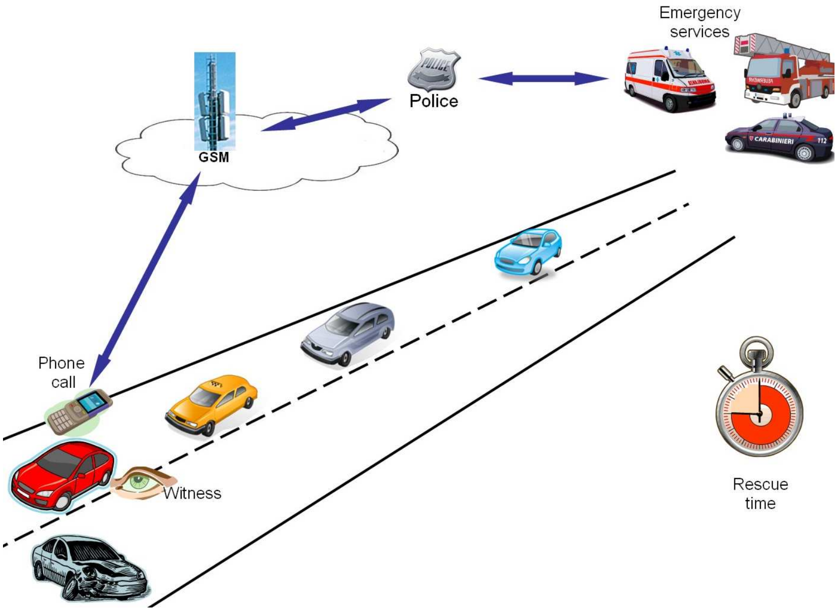


Figure 2.2: Old method of rescue using a cellular phone when an accident occurred.

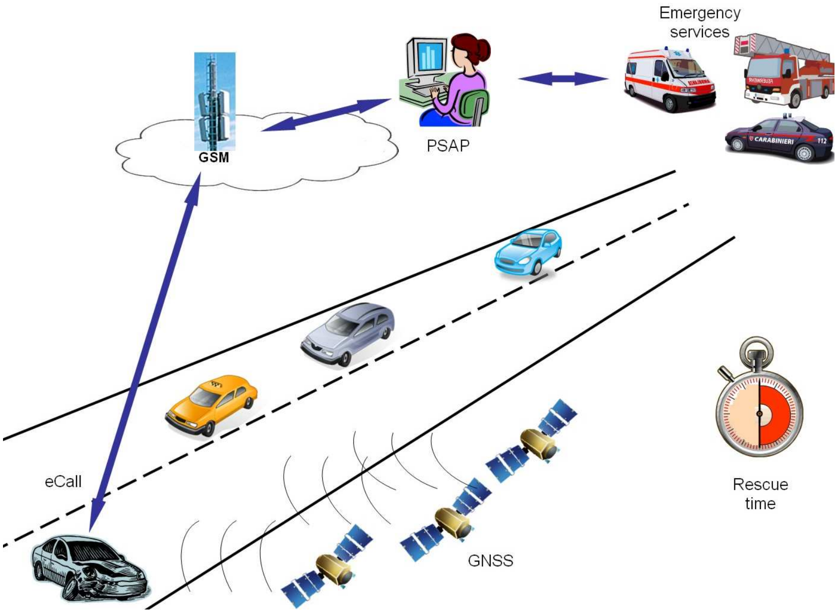


Figure 2.3: Current method of rescue when an accident occurs (e.g. eCall and OnStar).

coming from an in-vehicle eCall device. They must also be able to process the MSD, including location data, which is automatically transmitted by the eCall system, even when voice communication is not possible.

The content of the MSD includes: (a) control information, (b) VIN (Vehicle Identification Number), (c) time, (d) latitude, (e) longitude, and (f) direction. The recommended transmission of the MSD between the OBU in the car and the PSAP requires a parallel data transmission with voice. Whether the call is made manually or automatically, there will always be a voice connection between the vehicle and the rescue center. In this way, any car occupants capable of answering questions can provide additional details about the accident.

For eCall to work, several requirements [Eur08] must be met: Firstly, all newly manufactured cars will have to be equipped with eCall devices. In 2005, the European Commission and the automotive industry association agreed to schedule full-scale deployment of eCall service for 2009. eCall devices were made available as an option for all new cars, on September 2009.

Secondly, there is a need for the single European emergency number 112 to be operational for both fixed and mobile calls throughout the European Union. Unfortunately, not all EU member states are able to support the full 112 emergency services. Presently, the eCall system is working in 12 out of 27 EU member states.

Thirdly, emergency centers and all rescue services must be capable of processing the accident location data transmitted by eCalls. For example, ambulances must be adequately capable of receiving and processing these data. Rescue centers must be able to forward all the information to the fire brigade, hospital emergency rooms, etc. In addition, to take full advantage of the voice link to the crashed vehicle, rescue center personnel must be properly trained so as to gather critical information in several languages.

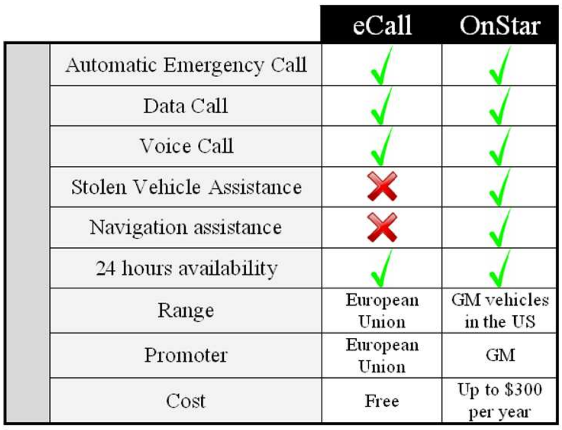
Essentially, by knowing the exact location of the crash site, response time of emergency services can be reduced by 50% in rural and 40% in urban areas. Due to this time reduction, eCall is expected to save up to 2,500 lives in the EU each year, while at the same time mitigating the severity of tens of thousands of injuries. Since eCall can also accelerate the treatment of injured people, there will be better recovery prospects for accident victims. In addition, earlier arrival at the accident scene will also translate into faster clearance of the crash site, which helps to reduce road congestion, fuel waste, and CO2 emissions. Overall, it aids in our quest for a greener and safer environment.

2.5.1 Comparison of eCall and OnStar

OnStar [ons09] is an in-vehicle safety and security system created by General Motors (GM) for on-road assistance. Both eCall and OnStar systems are, in fact, very similar. A vehicle collision activates on-vehicle sensors, causing an emergency voice call to be initiated. Also, key information about the accident is transmitted.

Unlike eCall, OnStar provides an on-road navigation system and assistance in case the vehicle is stolen; it can also remotely unlock vehicles. Nevertheless, eCall is more ambitious since it is expected to support all brands of vehicles in the European Union region, while OnStar is only supported by GM vehicles in the US. Table 2.11 outlines the most important differences between eCall and OnStar.

Table 2.11: eCall VS. OnStar



	eCall	OnStar
Automatic Emergency Call	✓	✓
Data Call	✓	✓
Voice Call	✓	✓
Stolen Vehicle Assistance	✗	✓
Navigation assistance	✗	✓
24 hours availability	✓	✓
Range	European Union	GM vehicles in the US
Promoter	European Union	GM
Cost	Free	Up to $300 per year

Future accident notification systems will be more ambitious; intelligent systems will automatically adapt the required rescue resources, allowing the rescue staff to work more efficiently, and reducing the time associated with their tasks.

2.6 A View on Future Emergency Services

In the future, our current accident notification paradigm will change with the introduction of vehicular networks. By combining V2V and V2I communications, new Intelligent Transportation Systems will emerge, capable of improving the timeliness and responsiveness of roadside emergency services. As shown in Figure 2.4, the accident information gathered can be delivered to a Control Unit (CU) that automatically estimates: (a) the severity of an accident, and (b) the appropriate rescue resources before summoning for emergency services.

Future emergency rescue architectures will exploit various communication technologies, such as DSRC, UMTS/HSDPA, and WAVE, empowering road users with both localized (via VANETs) and long haul (via cellular or wide area wireless data) wireless communications. By using vehicular communications, cars involved in an accident can send alerts and other important information about the accident to near-by vehicles and to the nearest wireless base station. Thereafter, an intelligent PSAP will gather this information, and channel the most critical data to the appropriate emergency services. Vehicular networks can allow faster notification of any accident occurring on the road (since sensing and propagation of incident information is done on-the-spot in real-time via multi-hop V2V communications). Surrounding vehicles will be immediately notified of the hazard, and such alerts can be further propagated via radio base stations to the core network.

Concerning technology, for any proposal to be successful, it should be compatible with the signaling protocol and air interfaces of existing implementations or standardizations. So, V2V communications should be compatible with the future 802.11p standard, while the V2I counterpart might use any of the 3/4G cellular

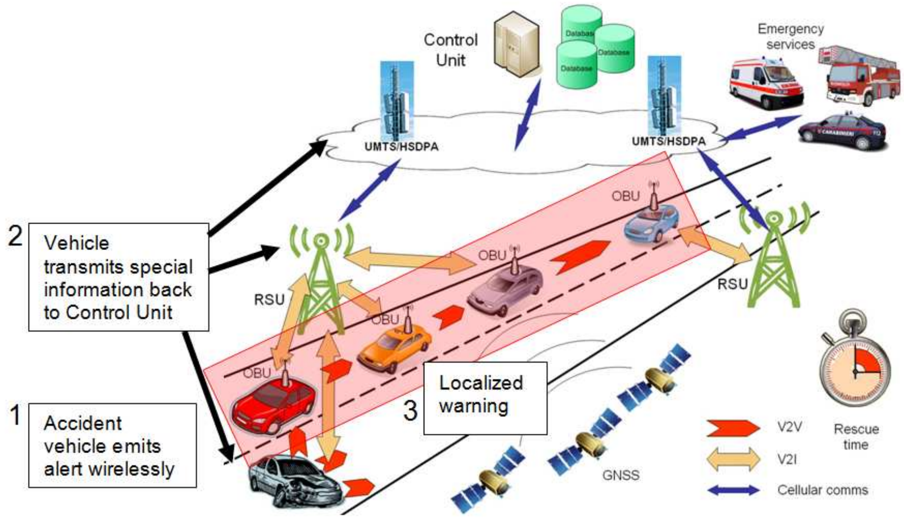


Figure 2.4: Future emergency rescue architecture combining V2I and V2V communications, combining localized alerts and warnings, special control information transmission, intelligent databases, and a Control Unit.

technologies currently available. The usage of hybrid multi-wireless platforms adds robustness and reliability to the call for emergency help and rescue. In the near future, a community-based effort involving the state departments, public organizations and industry is needed to deploy the required technology and infrastructure to connect all the vehicles on the road and the emergency services.

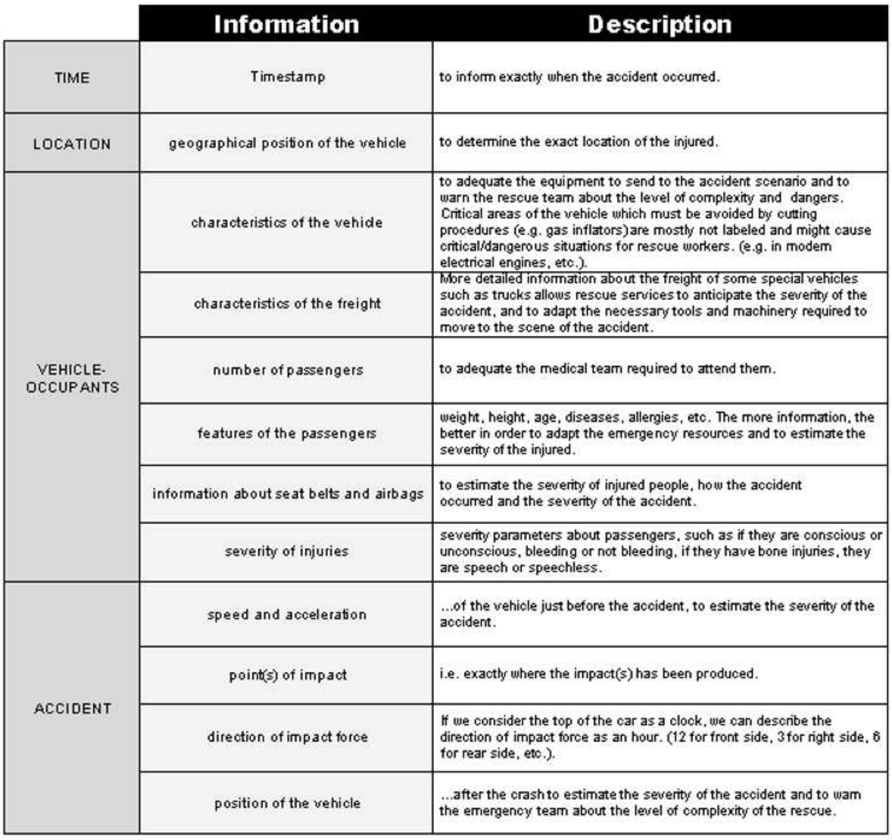
2.6.1 Data for Emergency Use in the Future

Rescue services currently do not have any vehicle-specific information available at the scene of the accident. Rescue manuals provided by some vehicle manufacturers contain too much information to be remembered by rescue staffs under critical situations. The electronic on-board systems currently provide standardized information in a consistent format for all manufacturers. However, the vehicle selection process should be improved so that rescue staff can select the correct vehicle model using the license plate number or the Vehicle Identification Number (VIN) number.

In terms of the vehicle information system, current electronic information systems only offer static information, which shows the state of different components in the car. Automatic identification of the vehicles involved is only possible in certain countries, for instance via a license plate request (Netherlands, Sweden) or by entering the VIN (USA). There is no connection to Automatic Crash Notification systems, which should also be capable to select the correct vehicle information and show detailed information about the accident characteristics. In the near future, all these issues shall be addressed.

With knowledge about the crash and related injury severity of occupants, the

Table 2.12: Information to be sent after an accident



	Information	Description
TIME	Timestamp	to inform exactly when the accident occurred.
LOCATION	geographical position of the vehicle	to determine the exact location of the injured.
VEHICLE-OCCUPANTS	characteristics of the vehicle	to adequate the equipment to send to the accident scenario and to warn the rescue team about the level of complexity and dangers. Critical areas of the vehicle which must be avoided by cutting procedures (e.g. gas inflators)are mostly not labeled and might cause critical/dangerous situations for rescue workers. (e.g. in modern electrical engines, etc.).
	characteristics of the freight	More detailed information about the freight of some special vehicles such as trucks allows rescue services to anticipate the severity of the accident, and to adapt the necessary tools and machinery required to move to the scene of the accident.
	number of passengers	to adequate the medical team required to attend them.
	features of the passengers	weight, height, age, diseases, allergies, etc. The more information, the better in order to adapt the emergency resources and to estimate the severity of the injured.
	information about seat belts and airbags	to estimate the severity of injured people, how the accident occurred and the severity of the accident.
	severity of injuries	severity parameters about passengers, such as if they are conscious or unconscious, bleeding or not bleeding, if they have bone injuries, they are speech or speechless.
ACCIDENT	speed and acceleration	...of the vehicle just before the accident, to estimate the severity of the accident.
	point(s) of impact	i.e. exactly where the impact(s) has been produced.
	direction of impact force	If we consider the top of the car as a clock, we can describe the direction of impact force as an hour. (12 for front side, 3 for right side, 6 for rear side, etc.).
	position of the vehicle	...after the crash to estimate the severity of the accident and to warn the emergency team about the level of complexity of the rescue.

work of paramedics and physicians can be improved in a significant way. The first step of treatment can be initiated by retrieving information about the status of occupants. Preliminary research work has been done in the U.S. by the "William Lehman Injury Research Center" [Wil09]. The URGENCY algorithm was developed to predict the injury risk based on observed data from the vehicle or from the paramedic.

Regarding information to be sent after an accident, Table 2.12 shows our proposal. We think that the information shown in this table is essential in future emergency services. Basically, the information to be sent after an accident should include the following: (a) the time when the accident has occurred, (b) the location of the vehicle to determine the location of the injured, (c) the characteristics of the vehicle (allowing rescue services to send appropriate equipment to the accident site, and to warn[1] them about the level of complexity and dangers), (d) the characteristics and identities[2] of the occupants, such as the number of passengers,

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[1] It is very important for rescuers to know which critical areas of the vehicle to avoid (e.g. gas inflators) since they are mostly not labeled and might cause hazards for rescue workers.

[2] The identities of the victims will help in determining their medical past history, while per-

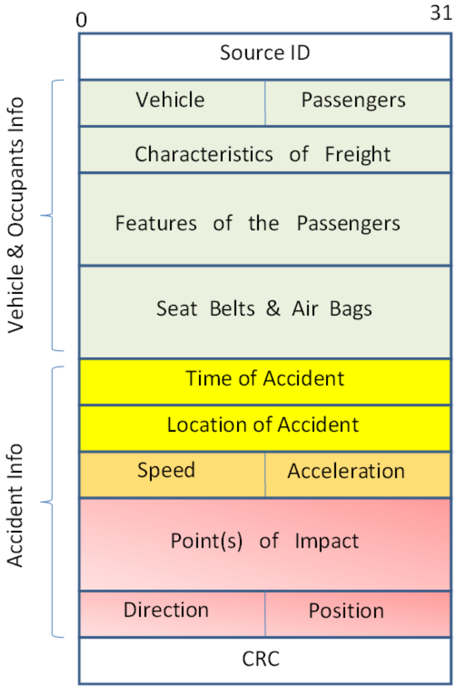

Figure 2.5: Essential information elements to be transmitted in future emergency services.

their features (height, weight, etc.), and the severity of their injuries are important pieces of information to be transmitted, and finally, (e) the characteristics of the accident, such as the speed and acceleration of the vehicle when the impact occurred, the points of impact, the direction of impact force, and the position of the vehicle after the impact. All these information help in determining the severity of the impact, making it possible to save lives, manage resources efficiently, and enable crashed vehicles to be removed from the site, restoring traffic flow quickly.

The information shown in Table 2.12 is made compatible with the standard CEN/TS 15722:2009 [CEN09], which defines the data content and format of the eCall messages. Figure 2.5 illustrates the SOS Packet Format that we propose. It includes all the aforementioned information in just 56 bytes. This information will be sent by each damaged vehicle, traveling along the vehicular network to the next RSU in order to arrive to the Control Unit (CU). All these data shall be automatically processed by the CU to decide the resources needed to correctly take care and manage the accident. The CU will compare the data received with

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mitting a fast identification of their family and relatives. The injuries should be coded using the Abbreviated Injury Scale (AIS) [CSCB89], an anatomical scoring system that provides a reasonably and accurate ranking of the severity of injury. In the AIS scale, injuries are ranked on a scale from 1 to 6, with 1, 5, and 6 representing minor, severe, and unsurvivable injury respectively.

previously collected data from a database of accidents, making it possible to predict the severity of injuries, and thus summoning the needed resources for the rescue. In 8 we will integrate this information into our proposed scheme for warning message dissemination in VANETs.

2.7 Summary

Several research projects led by research institutes and car manufacturers around the world have positively impacted the future of *Inter-Vehicle Communication* (IVC) systems. Technologies have clearly contributed to the change in the course of actions to follow after an accident occurs, moving from a simple cellular phone call made by a witness, to the current eCall accident notification system provided in EU.

In the near future, accident notification systems will be specially designed for post-collision rescue services. Combining V2V and V2I communications, new Intelligent Transportation Systems will emerge with the capability of improving the responsiveness of roadside emergency services, and allowing: (a) direct communication among the vehicles involved in the accident, (b) automatic delivery of accident related data to the Control Unit, and (c) an automatic and preliminary assessment of damages based on communication and information processing.

Future ITS-based emergency services aim at achieving a low level of fatalities while significantly improving the response time and efficient use of resources.

In this chapter, we examine the impact of future ITS technologies on road safety and emergency services, and we propose the essential information which will be disseminated by vehicles after an accident. In our thesis, we focus on vehicular networks in order to reduce the number of accidents. We propose and evaluate a novel protocol to improve the warning message broadcast effectiveness in safety applications for vehicular networks.

Chapter 3

Vehicular Ad Hoc Networks (VANETs)

The development of communication networks was a significant step for mankind, undoubtedly facilitating everyday's tasks and improving the quality of life. Both telecommunication and computer networks began with a strong emphasis on wires, both for the communications infrastructure and for the last hop where the actual connection towards the users' terminals takes place. In the last decade this trend has shifted towards wireless networks, especially at the user side. This shift comes from the demand of improved mobility support and greater flexibility, so as to face the challenges of our fast-changing society [Cal06].

Regarding vehicular environments, technology advances in the wireless networking field have contributed to supporting new services and applications for vehicular passenger safety and driver assistance. This chapter presents an overview of the current state-of-the-art in terms of vehicular wireless technologies and standards that will be widely adopted by industry in the next years. We also review the existing broadcast storm reduction schemes, and the related work on dissemination of warning messages in VANETs.

3.1 Introduction

Mobile ad hoc networks (MANETs) are a type of wireless network that does not require any fixed infrastructure. MANETs are attractive for situations where communication is required, but deploying a fixed infrastructure is impossible.

Vehicular ad hoc networks (VANETs) are a subset of MANETs, and represent a rapidly emerging research field considered essential for cooperative driving among communicating vehicles. Vehicles function as communication nodes and relays, forming dynamic networks with other near-by vehicles on the road and highways. While *Mobile ad hoc Networks* (MANETs) are mainly concerned with mobile laptops or wireless handheld devices, VANETs are concerned with vehicles (such as cars, vans, trucks, etc). Figure 3.1 shows and example of a VANET in a urban

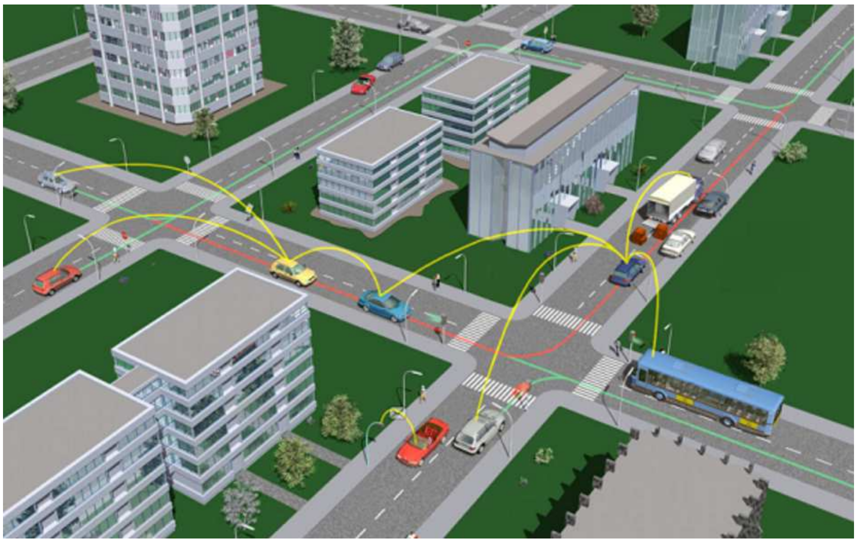


Figure 3.1: Example of a VANET.

scenario, where cars communicate in a multi-hop fashion.

Wireless technologies such as *Dedicated Short Range Communication* (DSRC) [XSMK04] and the IEEE 802.11p *Wireless Access for Vehicular Environment* (WAVE) [Eic07] enable peer-to-peer mobile communication among vehicles (V2V) and communication between vehicles and the infrastructure (V2I), and are expected to be widely adopted by the car industry in the next years.

To date, many solutions regarding VANETs have been proposed and evaluated via simulation. Nevertheless, the simulation environments used to be very simplistic, so utilizing more realistic simulation environments is required.

This chapter is organized as follows: Section 3.2 introduces the most important characteristics and the different applications of VANETs. Section 3.3 gives an overview of the available IEEE Wireless Access in Vehicular Environments (WAVE) standards. Section 3.4 introduces the existing Broadcast Storm Reduction schemes. Section 3.5 presents some related work on message dissemination protocols, and on collision prevention mechanisms in VANETs. Finally, Section 3.6 concludes this chapter.

3.2 Characteristics and Applications of VANETs

VANETs are characterized by: (a) trajectory-based movements with prediction locations and time-varying topology, (b) variable number of vehicles with independent or correlated speeds, (c) fast time-varying channel conditions (e.g., signal transmissions can be blocked by buildings), (d) lane-constrained mobility patterns (e.g., frequent topology partitioning due to high mobility), and (e) reduced power consumption requirements. So far, the development of VANETs is backed by

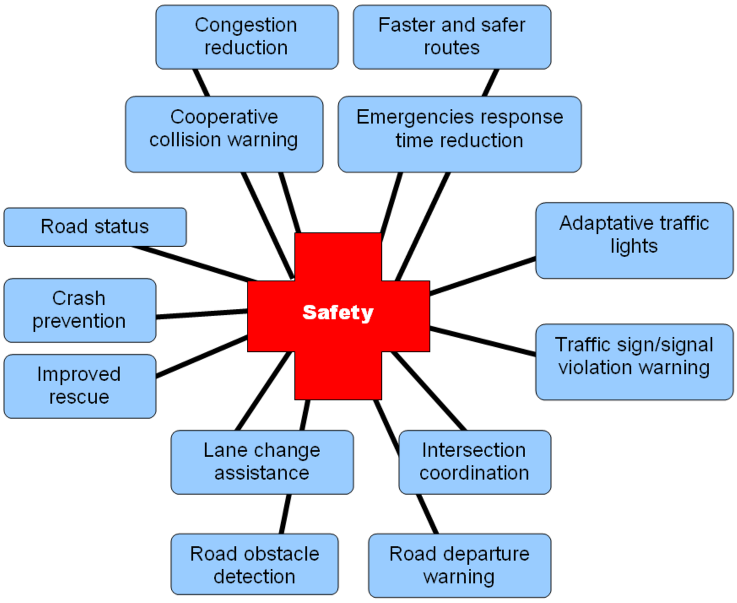


Figure 3.2: Traffic safety applications of VANETs.

strong economical interests since vehicle-to-vehicle (V2V) communication allows using wireless channels for collision avoidance (improving traffic safety), improved route planning, and better control of traffic congestion [BFW03].

The specific characteristics of Vehicular networks favor the development of attractive and challenging services and applications. These applications can be grouped together into two main different categories:

- Safety applications (see Figure 3.2), that look for increasing safety of passengers by exchanging relevant safety information via V2V and V2I communications, in which the information is either presented to the driver, or used to trigger active safety systems. These applications will only be possible if the penetration rate of VANET-enabled cars is high enough. In this thesis, we will focus in safety applications in order to reduce the number of fatalities while significantly improving the response time and the use of rescue resources.

- Comfort and Commercial applications (see Figure 3.3) that improve passenger comfort and traffic efficiency, optimize the route to a destination, and provide support for commercial transactions. Comfort and commercial applications must not interfere with safety applications [JK08].

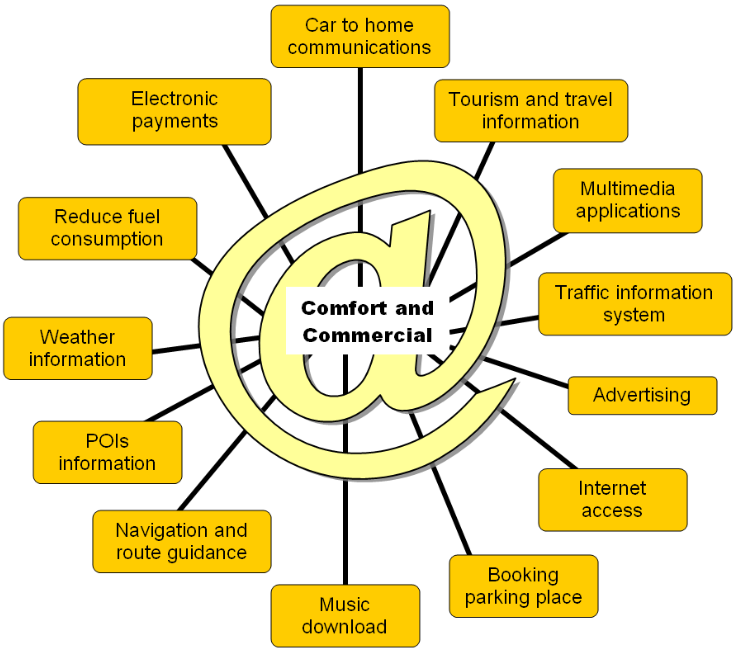


Figure 3.3: Comfort and commercial applications of VANETs.

3.3 Standards for VANETs

By 1996, the US Department of Transportation (DOT), the Intelligent Transportation Society of America (ITSA), and several other interested parties had developed a procedural framework wherein Intelligent Vehicle-Highway Systems (IVHS) services (or Intelligent Transportation System [ITS] services, as they are known today) could be systematically planned, defined, and integrated. Known as the National Intelligent Transportation Systems Architecture (NITSA), this framework has served as a master plan for ITS initiatives for the past 14 years.

From the beginning, the NITSA recognized wireless communications as a cornerstone for the implementation of many ITS services. At the time, some applications, such as automated toll collection, were performed using the spectrum between 902 MHz and 928 MHz. Unfortunately, this band was too small and polluted to enable the envisioned evolution of IVHS communications. Consequently, in 1997, the ITSA petitioned the Federal Communications Commission (FCC) for 75 MHz of bandwidth in the 5.9-GHz band with the specific goal of supporting Dedicated Short-Range Communications (DSRC) for ITS. The FCC granted the request in October of 1999. The DSRC-based ITS radio services received 75 MHz of spectrum in the 5.85-5.925 GHz range. The frequency band is divided into 7 channels as shown in Figure 3.4.

By July 2002, the ITSA was actively lobbying the FCC on matters of licensing, service rules, and possible technologies for the ITS-DSRC band. The ITSA recommended the adoption of a single standard for the physical (PHY) and medium access control (MAC) layers of the architecture, and proposed one developed by the American Society for Testing and Materials (ASTM) based on the IEEE 802.11 (ASTM's E2213-02). The FCC officially adopted this recommendation in the 2003-2004 timeframe.

In 2004, the IEEE task group p of the IEEE 802.11 working group assumed the role initiated by the ASTM and started developing an amendment to the 802.11 standard to include vehicular environments. The document is known as IEEE 802.11p [Tas06]. Another IEEE team (working group 1609) undertook the task of developing specifications to cover additional layers in the protocol suite.

The IEEE 1609 standards set consisted of four documents: the IEEE 1609.1 [IEE06a], the IEEE 1609.2 [IEE06b], the IEEE 1609.3 [IEE07], and the IEEE 1609.4 [IEE06c]. Collectively, IEEE 802.11p [Tas06] and IEEE 1609.x are called wireless access in vehicular environments (WAVE) standards because their goal, as a whole, is to ease the provision of wireless access in vehicular environments. The conceptual design they portray is called WAVE architecture, and the systems that implement it are referred to as WAVE systems. Next, we give an overview of the IEEE WAVE standards.

3.3.1 Wireless Access in Vehicular Environments (WAVE)

A WAVE system is a radio communications system intended to provide seamless, interoperable services to transportation. These services include those recognized by the U.S. National Intelligent Transportation Systems (ITS) Architecture and many others contemplated by the automotive and transportation infrastructure industries. These services include vehicle-to-roadside as well as vehicle-to-vehicle communications, generally over line-of-sight distances of less than 1000 m, where the vehicles may be moving at speeds up to 140 km/h. Networking services provide data delivery between WAVE devices and management services to all the layers.

The scope of the WAVE standards is to define services, operating at the network and transport layers, that support wireless connectivity among vehicle-based devices, and between fixed roadside devices and vehicle-based devices, using the 5.9 GHz DSRC/WAVE mode. The protocol architecture defined by these standards is shown in Figure 3.5.

The overall WAVE architecture includes the following standards: (i) IEEE 1609.1, (ii) IEEE 1609.2, (iii) IEEE 1609.3, (iv) IEEE 1609.4, and (v) IEEE

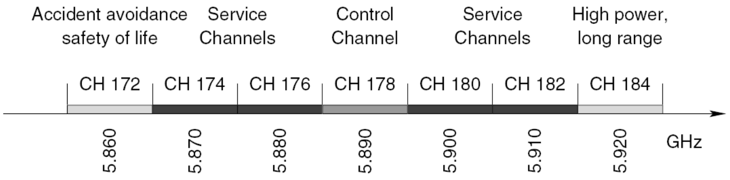


Figure 3.4: Channels available for DSRC [Eic07].

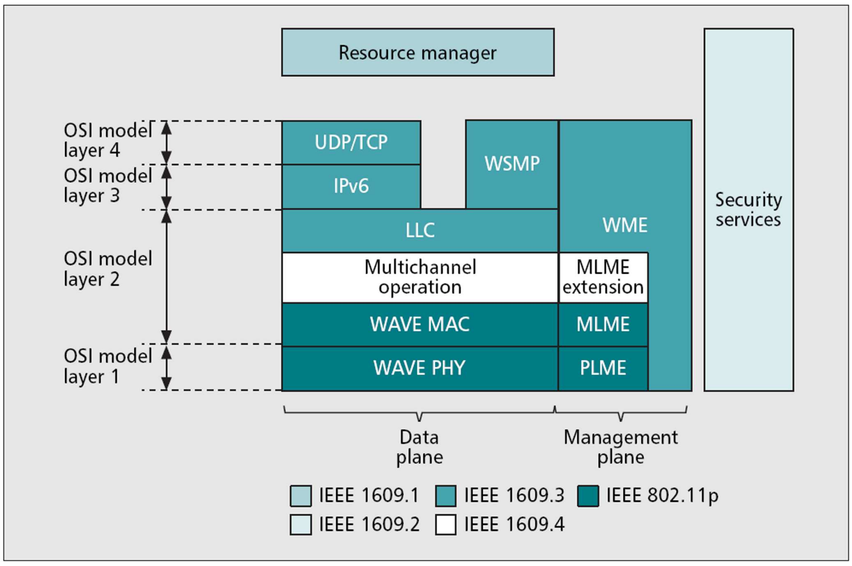


Figure 3.5: WAVE communications protocol stack indicating the standard that covers each set of layers. The blocks marked as "Resource manager" and "Security services" do not fit easily within the layered structure of the OSI model [UDSAM09].

802.11p. The IEEE 1609.1 defines an application, the Resource Manager, that uses the network stack for communications. The IEEE 1609.2 defines security, secure message formatting, processing, and message exchange. Channelization and the upper layers of the network stack are defined in IEEE 1609.4 and IEEE 1609.3, respectively. The Physical Layer (PHY) and the Medium Access Control (MAC) protocol are based on the IEEE 802.11 PHY and MAC standards, and are defined by the IEEE 802.11p.

3.3.2 Components of a WAVE System

In a WAVE system, there are two types of devices (see Figure 3.6): roadside units (RSUs) and onboard units (OBUs). An RSU is a WAVE device that operates at a fixed position (usually along roads) and that supports communication and data exchange with OBUs. Roadside units are usually installed in light poles, traffic lights, or road signs (see Figure 3.7). An OBU is a mobile or portable WAVE device that supports information exchange with RSUs and other OBUs. Onboard units are mounted in vehicles and can work while moving (see Figure 3.8).

By default, WAVE units operate independently, exchanging information over a fixed radio channel known as the control channel (CCH). However, they can also organize themselves in small networks called WAVE basic service sets (WBSSs), which are similar in nature to the service sets defined in IEEE 802.11. WBSSs can consist of OBUs only, or a mix of OBUs and RSUs (see Figure 3.6). All the

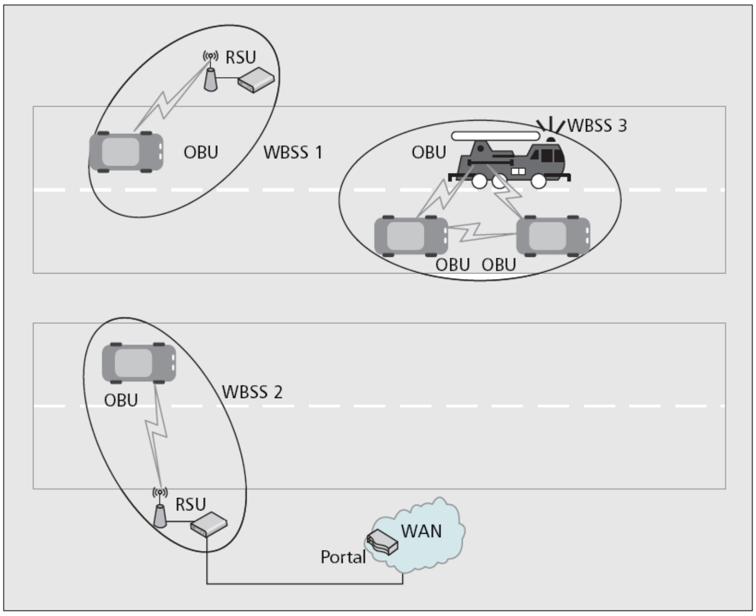


Figure 3.6: Illustration of a WAVE system showing the typical locations of the OBUs and RSUs, the general makeup of the WBSSs, and the way a WBSS can connect to a WAN through a portal [UDSAM09].

Figure 3.7: Example of an RSU installation.

Figure 3.8: Example of an OBU.

members of a particular WBSS exchange information through one of several radio channels known as service channels (SCHs). Through the appropriate portals, a WBSS can connect to a wide-area network.

Upon startup, a device monitors the control channel until a WAVE service advertisement (WSA) is received that announces a service that utilizes a SCH, or the device chooses to utilize the SCH based on the WAVE announcement frames it transmits. WAVE devices must also monitor the CCH for additional safety or private service advertisements during specific intervals known as control channel intervals (CCH intervals). If suspension of transactions in progress on a SCH is necessary when CCH monitoring is required, the data exchange may be resumed when CCH monitoring is no longer required (i.e., when the device can return to the SCH). This may occur, for example, with a single channel device that can perform exchanges on only one radio frequency (RF) channel at a time; in this case, it is recommended implementing a method to support buffering data packets while monitoring the CCH, until the device can return to the SCH to complete the transactions in progress.

To accommodate devices that want to exchange data on SCHs, but that can not monitor the CCH while doing so, synchronization is necessary. Synchronization is the procedure by which a device adopts the time reference of another source of time. In addition to being synchronized to each other, such devices must also know when it is permissible to cease monitoring the CCH. With this purpose, CCH and SCH intervals are uniquely defined with respect to an absolute external time reference, Coordinated Universal Time (UTC). UTC is commonly provided by Global Positioning Systems (GPS); however, the time base accuracy requirements for WAVE devices are sufficiently lenient that management frames containing UTC time estimates from other devices can be used as well. Once synchronized, single-channel devices can ensure they meet the requirement to be monitoring the CCH during specified CCH intervals. It is important to note that synchronization is not required to make data exchanges on SCHs. While synchronization is optional, internal time base generation is required for security purposes.

3.3.3 Communication Protocols

The WAVE architecture supports two protocol stacks: (i) traditional Internet Protocol version six (IPv6), and (ii) a proprietary one known as WAVE Short-Message Protocol (WSMP), as shown in Figure 3.5. In the terminology of the OSI model, both stacks use the same physical and data-link layers, and they differ from each other in the network and transport layers. The WAVE standards do not specify session, presentation, or application layers. However, they do introduce two elements that do not fit easily within the boundaries of the OSI model: the resource manager and the security services blocks.

The reason for having two protocol stacks is to accommodate high-priority, time-sensitive communications, as well as more traditional and less demanding exchanges, such as Transmission Control Protocol/User Datagram Protocol (TCP / UDP) transactions. WSMP enables the application to send short messages and it directly controls certain parameters of the radio interface to maximize the probability that all parties involved will receive the messages in time. However, WSMP is not enough to support typical Internet applications, and these are required to attract private investment that would help spread, and ultimately reduce the cost of implementing the systems; hence the inclusion of IPv6.

As previously referred, the WAVE architecture is based on the IEEE 802.11 standard, which specifies layer one and part of layer two of the protocol stack. Given the differences between the operating environment of an 802.11 wireless local area network (WLAN) and a vehicular environment, an amendment to the standard was required, which is known as IEEE 802.11p. This norm specifies not only the data transmission portion of the protocols, but also the management functions associated with the corresponding layer (the physical layer management entity [PLME] and the MAC layer management entity [MLME] blocks).

Unlike traditional wireless LAN stations, WAVE units might be required to divide their time between the CCH and the SCHs. Therefore, the WAVE protocol stack includes a sublayer at OSI layer two, dedicated to controlling this multichannel operation. This sublayer (including the associated management functions) is specified in IEEE 1609.4. The remaining part of OSI layer two (the logical link control [LLC]) follows the IEEE 802.2 standard. At the level of the OSI layers three and four, IEEE 1609.3 specifies the aforementioned WSMP and explains how to incorporate traditional IPv6, UDP, and TCP in the systems. That document also defines a set of management functions (labeled as WAVE management entity [WME] in Figure 3.5) that must be used to provide networking services. The remaining two blocks (resource manager and security services) do not fit easily in the layered structure of the OSI model. They are covered by IEEE 1609.1 and IEEE 1609.2, respectively.

In the next subsections we briefly present the different IEEE standards included in the WAVE architecture.

3.3.4 IEEE 1609.1

This standard specifies the WAVE application known as the Resource Manager (RM), which resides, on the RSU, and its peer, known as the Resource Command Processor (RCP), which resides on the OBU. Remote applications, known as Resource Manager Applications (RMAs), communicate with the RCP through the RM. This standard describes how the RM multiplexes requests from multiple RMAs, each of which is communicating with multiple OBUs hosting an RCP. The purpose of the communication is to provide the RMAs access to "resources" such as memory, user interfaces (UIs), and interfaces to other onboard equipment controlled by the RCP, in a consistent, interoperable, and timely manner to meet the requirements of RMAs.

The RM uses the concept of all of the communication being initiated from an entity known as a provider, which issues requests to an entity known as a user, that only responds to the requests received. Within this standard, the RM is the provider of a service (as a representative of the RMAs), and the RCP the user of a service (representing the resources to be managed). Either the RSU or the OBU can operate as the provider; in other words, either device type can host the RM. The device that is hosting the RM (RSU or OBU) will be referred to as the provider device.

The scope of this standard is to specify the services and interfaces of the WAVE RM, including protective mechanisms for security and privacy, applicable and available to all users of DSRC and WAVE mode operations in the 5.9 GHz band authorized by the Federal Communication Commission (FCC) for intelligent transportation systems (ITS). The purpose of this standard is to enable complete interoperability of applications using WAVE in a manner that simplifies the onboard vehicle systems, reducing cost and improving performance. Effective use of the memory pages by applications can also minimize configuration management issues over the lifetime of a system.

3.3.5 IEEE 1609.2

The IEEE 1609.2 document specifies security services for the WAVE networking stack and for applications that are intended to run over that stack. Services include encryption using another party's public key, and non-anonymous authentication.

The scope of this standard is to define secure message formats, and the processing of those secure messages, within the DSRC/WAVE system. The standard covers methods for securing WAVE management messages and application messages, with the exception of vehicle-originating safety messages. It also describes administrative functions necessary to support the core security functions. It is anticipated that vehicle-originating safety messages will be added in an amendment to this standard.

The safety-critical nature of many DSRC/WAVE applications makes it vital that services be specified that can be used to protect messages from attacks such as eavesdropping, spoofing, alteration, and replay. Additionally, the fact that the wireless technology will be deployed in personal vehicles, whose owners have a right to privacy, means that the security services must be designed to respect that right as much as possible, and not leak personal, identifying, or linkable information to unauthorized parties.

3.3.6 IEEE 1609.3

WAVE networking services provide Logical Link Control (LLC), network, and transport layer functions. The general WAVE protocol stack, from the perspective of WAVE networking services, is shown in Figure 3.5. The IEEE 1609.3 defines routing and transport services, providing an alternative to IPv6. The stack consists of the following:

- Data plane, which contains the communication protocols and hardware used for delivering data. The data plane carries traffic primarily generated by, or destined for, applications. It also carries traffic between management plane entities on different machines, or between management plane entities and applications (e.g., for notification). Throughout this document, descriptions assume that all the WAVE protocol entities reside in a single physical device, but this need not be the case.

- Management plane, which performs system configuration and maintenance functions. Management functions employ the data plane services to pass management traffic between devices. Specific Management Entities are defined for certain individual layers, e.g., physical layer management entity (PLME), and MAC layer management entity (MLME). The WAVE management entity (WME) is a more general collection of management services. Note that the WME provides its management interface to all data plane entities, including WSMP (see Figure 3.5).

3.3.7 IEEE 1609.4

This standard describes multi-channel wireless radio operations, WAVE mode medium access control (MAC) and physical layers (PHYs), including the operation of control channel (CCH) and service channel (SCH) interval timers, parameters for priority access, channel switching and routing, management services, and primitives designed for multi-channel operations.

The purpose of the IEEE 1609.4 is to enable effective mechanisms that control the operation of upper layers across multiple channels, without requiring knowledge of PHY parameters, and describe the multi-channel operation and switching for different scenarios.

The services provided by this standard are used to manage channel coordination and to support MAC service data unit (MSDU) delivery. The channel routing service controls the routing of data packets from the LLC to the designated channel within channel coordination operations in the MAC layer. The channel coordination service coordinates the channel intervals according to the channel synchronization operations of the MAC layer, so that data packets from the MAC are transmitted on the proper RF channel.

IEEE 1609.4 supports a variety of safety and non-safety applications with up to 8 levels of priority as defined in IEEE 1609.3 and IEEE 802.11-REVma. The user priority (UP) is used to contend for medium access using Enhanced Distributed Channel Access (EDCA) functionality derived from IEEE 802.11-REVma.

3.3.8 IEEE 802.11p

IEEE 802.11p is a draft amendment to the IEEE 802.11 standard to add *Wireless Access in the Vehicular Environment* (WAVE). It defines enhancements to 802.11 required to support *Intelligent Transportation Systems* (ITS) applications. This includes data exchange between high speed vehicles and between vehicles and roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz). IEEE 1609 is a higher layer standard on which IEEE 802.11p is based.

The 802.11p will be used as the groundwork for *Dedicated Short Range Communications* (DSRC), a U.S. Department of Transportation project based on the ISO Communications, Air-interface, Long and Medium range (CALM) architecture standard looking at vehicle-based communication networks, particularly for applications such as toll collection, vehicle safety services, and commerce transactions via cars. The ultimate vision is a nationwide network that enables communications between vehicles and roadside access points or other vehicles. This work builds on its predecessor ASTM E2213-03.

WAVE devices shall be able to accommodate an architecture that supports a CCH and multiple SCHs. The CCH is used to transmit WSMs and announce WAVE services; the SCHs are used for application interactions/transmissions. The specific designations of these channels and the specification of the PHY are defined in IEEE 802.11p.

The WAVE stack uses a modified version of the IEEE 802.11a for its MAC and PHY layers known as the IEEE 802.11p. Note that, as in IEEE 802.11a, at a frequency of 5.9 GHz (i.e., the frequency band of the 802.11p standard), the signal will be 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 the vehicles are in line-of-sight.

The 802.11p MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA), and *Quality of Service* (QoS) extensions. Therefore, application messages are categorized into different *Access Categories* (ACs), where AC0 has the lowest, and AC3 the highest priority.

The 802.11p Task Group is still active. According to the official IEEE 802.11 Work Plan predictions, the approved 802.11p amendment is scheduled to be published in November 2010.

Recently, the European Commission has allocated the 5.9 GHz band for road safety applications, and both inter-vehicle and infrastructure communications. The intention is that compatibility with the USA systems will be ensured even if the allocation is not exactly the same; frequencies will be sufficiently close to enable the use of the same antenna and radio transmitter/receiver.

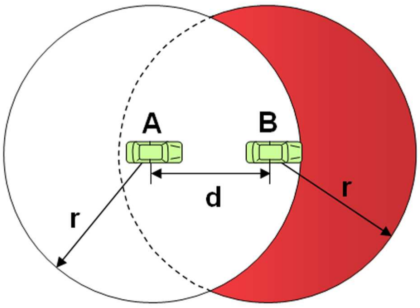


Figure 3.9: Additional coverage area (solid area) that can benefit from a rebroadcast: vehicle A sends a broadcast packet and vehicle B decides to rebroadcast the packet ($d < r$).

3.4 Existing Broadcast Storm Reduction Schemes

In VANETs, intermediate vehicles act as message relays to support end-to-end vehicular communications. For applications such as route planning, traffic congestion control, and traffic safety, flooding of broadcast messages commonly occurs. However, flooding can result in many redundant rebroadcasts, heavy channel contention, and long-lasting message collisions [TNCS02].

Over the years, several schemes have been proposed to address the broadcast storm problem in wireless networks, particularly in *Mobile ad hoc Networks* (MANETs) and *Wireless Sensor Networks* (WSNs). In the following subsections, we present the most interesting ones.

3.4.1 Counter-based

The *Counter-based scheme* [TNCS02] was introduced to mitigate the broadcast storm problem in MANETs. This scheme uses a threshold C, and a counter c to keep track of the number of times the broadcast message is received. Whenever $c \geq C$, rebroadcast is inhibited.

3.4.2 Distance-based

The *Distance-based scheme* was also presented in [TNCS02]. In this scheme, the authors use the relative distance d between vehicles to decide whether to rebroadcast or not. It is demonstrated that when the distance d between two vehicles is short, the *additional coverage* (AC) of the new rebroadcast is lower, and so rebroadcasting the warning message is not recommended. If d is larger, the additional coverage will be larger.

To estimate the distance between the source vehicle and the destination one, the signal strength of each received message can be used. Figure 3.9 shows an example of the AC area (solid area).

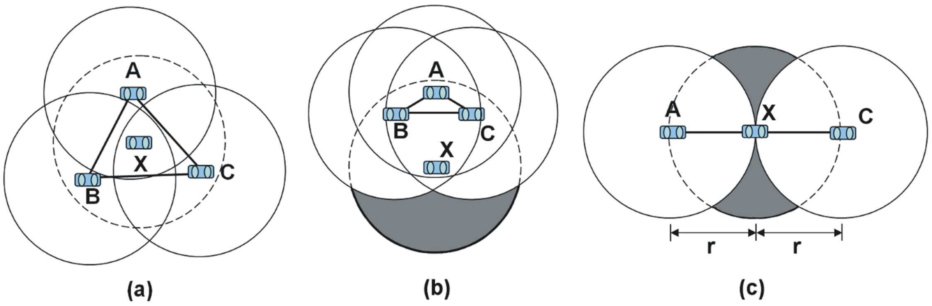


Figure 3.10: Scenarios of using convex polygons to determine whether to rebroadcast or not. (a) Vehicle X is inside the triangle formed by three sending vehicles. (b) Vehicle X is outside of the polygon. (c) Analysis of maximum loss of additional coverage on using the polygon test.

3.4.3 Location-based

The *Location-based scheme* presented in [TNCS02] is very similar to the distance-based scheme, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation (with convex polygons) of the AC of a warning message.

Since vehicles usually have GPS systems on-board, it is possible to estimate the additional coverage more precisely. Figure 3.10 shows three examples of the geometrical estimation of the AC area (solid area). The main drawback for using this scheme is the high computational cost of calculating the AC, which is related to calculating many intersection areas among several circles.

Note that all the aforementioned schemes alleviate the broadcast storm problem by inhibiting certain vehicles from rebroadcasting, reducing message redundancy, channel contention, and message collisions. All try to inhibit vehicles from rebroadcasting when the *additional coverage* (AC) area is very low. In [TNCS02], the authors demonstrated that a rebroadcast can only provide up to 61% additional coverage over that already covered by the previous transmission (41% additional area on average).

3.4.4 Cluster-based

The aforementioned schemes are based on statistical and geometric modeling to estimate the additional coverage of a rebroadcast. Cluster-based schemes apply the clustering concept. Note that clustering techniques have been used to solve other problems in MANETs (e.g., traffic coordination [GT95], routing [GT95], and fault-tolerance [AVC95]).

It is assumed that a host periodically sends packets to advertise its presence. Thus, any host can determine its connectivity with other hosts on its own. Each host has a unique ID. A cluster is a set of hosts formed as follows. A host with a local minimal ID will elect itself as a cluster head. This head host, together with its neighbors, will form a cluster. These neighbor hosts are called members of the cluster. Within a cluster, a member that can communicate with a host in another cluster is a gateway. To take mobility into account, when two heads meet, the one with a larger ID gives up its head role.

In such schemes, we assume that clusters have been formed in the VANET and will be maintained regularly by the underlying cluster formation protocol. In a cluster, the head's rebroadcast can cover all other hosts in that cluster, if its transmission experiences no collision. Apparently, to propagate the broadcast message to hosts in other clusters, gateway hosts should take the responsibility.

This approach is very promising to efficient broadcasting in high density urban scenarios, although to maintain the cluster information about all the vehicles is a hard task, especially in VANETs where frequent topology partitioning due to high mobility is present.

3.4.5 Smart Gossip Scheme

The *Smart Gossip scheme* presented in [KCG06] is a probabilistic protocol that offers a broadcast service with low overheads. Smart Gossip dynamically adapts transmission probabilities based on the underlying network topology. It is specially designed for WSNs where the broadcast service should minimize energy consumption. Nevertheless, vehicular networks have different topology and communication characteristics, so this scheme does not fit well in VANETs.

3.4.6 Weighted p-persistence, Slotted 1-persistence, and Slotted p-persistence

The *weighted p-persistence*, the *slotted 1-persistence*, and the *slotted p-persistence* techniques presented in [WTP+07] are some of the few proposed rebroadcast schemes for VANETs.

These three probabilistic and timer-based broadcast suppression techniques are not designed to solve the broadcast storm problem, but they can mitigate the severity of the storm by allowing nodes with higher priority to access the channel as quickly as possible. These schemes are specifically designed to be used in highway scenarios.

3.4.7 The Last One (TLO) Scheme

The TLO scheme, presented in [SP08], tries to reduce the broadcast storm problem finding the most distant vehicle from the warning message sender, so this vehicle will be the only allowed to retransmit the message. This method uses GPS information from the sender vehicle and the possible receivers to calculate the distance.

Although it brings a better performance than simple broadcast, this scheme is only effective in highway scenarios because it does not take into account the effect of obstacles (e.g. buildings) in urban radio signal propagation. Moreover, GPS information must be accurate to achieve good results, and it is not clearly stated how a vehicle knows the position of nearby vehicles at any given time.

The TLO approach was extended using a protocol which utilizes adaptive wait-windows and adaptive probability to transmit, named *Adaptive Probability Alert Protocol* (APAL) [SPC09]. This scheme shows even better performance than the TLO scheme, but it is also only validated in highway scenarios.

3.5 Dissemination of Warning Messages in VANETs

Previous research work on dissemination of warning messages in VANETs had focused on two issues: (a) message dissemination protocols, and (b) collision prevention mechanisms.

Regarding message dissemination protocols, Korkmaz et al. [KEOO04] proposed a new efficient IEEE 802.11 based *Urban Multi-hop Broadcast protocol* (UMB) which was designed to avoid hidden node and reliability problems of multi-hop broadcast in urban areas. They showed that this protocol has a very high success rate and efficient channel utilization when compared with other flooding based protocols. Torrent-Moreno et al. [TMSH05] studied the situation that arises when the number of nodes sending periodic safety messages in a specific area is too high. To achieve good performance, they proposed to limit the channel load by using a strict fairness criterion among nodes. Fasolo et al. [FZZ06] proposed a distributed position-based broadcast protocol, named *Smart Broadcast* (SB), that aims at maximizing the progress of the message along the propagation line, as well as minimizing the rebroadcast delay. Wischhof et al. [WER05] presented a novel method for scalable information dissemination in highly mobile ad hoc networks: *Segment-Oriented Data Abstraction and Dissemination* (SODAD). With SODAD, information can be distributed in an information range multiple orders of magnitude larger than the transmission range of the air interface, even if only less than 3% of all vehicles are equipped with an *Inter-Vehicular Communication* (IVC) system. More recently, Torrent-Moreno [TM07] proposed a position-based message forwarding strategy in order to disseminate time-critical safety information.

Regarding collision prevention mechanisms, Yang et al. [YLZV04] investigated ways to achieve low-latency in delivering emergency warnings under various road situations. They designed an effective protocol, comprising congestion control policies, service differentiation mechanisms and methods for emergency warning message dissemination. Their protocol removes unnecessary packet forwarding by checking for message duplicates at the application layer, though some authors [OKG06] think that it also requires local neighbor knowledge and additional application processing, which is difficult to acquire and maintain for collision avoidance protocols requiring low latency. Xu et al. [XSMK04] studied the design of layer-2 protocols for a vehicle to send safety messages to other vehicles. The target was to send safety messages with high reliability and low delay. They also explored the feasibility of sending safety messages from vehicle to vehicle using the DSRC control channel. Sengupta et al. [SRS$^+$06] focused on *Cooperative Collision Warning* (CCW) systems and presented experimental results showing the performance of a first prototyped CCW system. More recently, Zang et al. [ZSC$^+$07] studied the performance of the *Emergency Electronic Brake Light with Forwarding* (EEBL-F) application as an example safety application in congested scenarios.

To the best of our knowledge, only [WTP$^+$07] and [KEOO04] studied the broadcast storm problem related to warning message dissemination applications for VANETs. Moreover, only [YLZV04] and [ZSC$^+$07] focus on the new 802.11p standard for VANETs.

3.6 Summary

In this chapter we presented an overview of the current state-of-the-art of the vehicular wireless technologies that will be widely adopted by industry in the next few years. We also presented the different IEEE standards included in the WAVE architecture.

Afterwards we presented the most interesting schemes that have been proposed to address the broadcast storm problem in wireless networks, particularly in *Mobile ad hoc Networks* (MANETs) and *Wireless Sensor Networks* (WSNs), evidencing that the special characteristics of VANETs make it necessary to propose new schemes to cope with broadcast storm issues in these networks. Moreover, we made a brief review of previous research work on dissemination of warning messages in VANETs, focusing on two issues: (a) message dissemination protocols, and (b) collision prevention mechanisms.

Although more work is required, the foundations are laid to deploy V2I and V2V communication systems. There are clear evidences that it will be possible for our vehicles to communicate among them, or with traffic signs, very soon. This will put at drivers' disposal a number of services that will improve traffic safety, infotainment, and reduce road congestion, wastage of fuel and CO2 emissions.

Chapter 4

Simulation of VANETs

Deploying and testing VANETs involves high cost and intensive labor. Hence, simulation is a useful alternative prior to actual implementation. VANET simulation is fundamentally different from MANET (Mobile Ad Hoc Networks) simulation because, in VANETs, the vehicular environment imposes new issues and requirements, such as constrained road topology, multi-path fading and roadside obstacles, traffic flow models, trip models, varying vehicular speed and mobility, traffic lights, traffic congestion, and drivers' behavior. [BFW03].

In this chapter we present some of the existing Mobility Models proposed in the literature, since in VANET simulation is crucial the use of a realistic mobility model which reflects the real behavior of vehicular traffic. This chapter also presents a comprehensive study and comparison of publicly available VANET simulation software and their components. In particular, we contrast their software characteristics, *Graphical User Interfaces* (GUIs), popularity, ease of use, input requirements, output visualization capability, and accuracy of simulation. In addition, we also present the most relevant *Radio Propagation Models* (RPMs) available.

4.1 Introduction

Simulations of VANET often involve large and heterogeneous scenarios. Compared to MANETs, when we simulate VANETs, we must account for some specific characteristics found in vehicular environments.

One of the important issues when creating a simulation environment in VANETs is to correctly model how vehicles move, providing an accurate and realistic vehicular mobility description at both macroscopic and microscopic levels. Another challenge is to be able to dynamically alter this vehicular mobility as a consequence of the vehicular communication protocols. To date, many mobility models have been developed by the community in order to solve these two issues [HFB09].

Two other important aspects in VANETs are the loss of power density experienced by wireless signals as they propagate through a specific environment, and the signal absorption due to some obstacles in the environment, i.e., buildings, geographic conditions such as mountains, etc. Some Radio Propagation Models have been proposed by the community in order to address these two issues.

This chapter is organized as follows: Section 4.2 introduces the concept of *Mobility Model*, the different issues that a mobility model generator should include to generate realistic vehicular motion patterns. We also present a mobility models classification, the different mobility topologies used, and their importance to obtain accurate simulation results. Section 4.3 presents an overview of existing simulators for VANETs, discussing the various VANET mobility generators, network simulators, and VANET simulators currently available. The importance of simulation in VANETs motivates us to make a survey of existing VANET simulators in order to select the simulation tool to be used along this thesis. We will also identify some limitations of the available tools. In Section 4.4 we introduce the concept of *Radio Propagation Model* (RPM). In addition, we present the existing Radio Propagation Models, showing the limitations of existing attenuation and visibility schemes, respectively. In Section 4.5 we present the methodology followed to obtain the different simulation results, and the metrics we measured along this thesis. Finally, Section 4.6 concludes this chapter.

4.2 Mobility Models in VANETs

Based on previous studies of mobility behavior of mobile users [Toh01], existing models try to closely represent the movement patterns of users. These models provide a suitable environment for the simulation and evaluation of ad hoc communication performance. Moreover, it is well known that mobility models can significantly affect simulation results.

For results to be useful, it is important that the simulated model is as close to reality as possible [CSS02]. For MANETs, the random waypoint model (RWP) is by far the most popular mobility model [YLN03]. However, in vehicular networks, nodes (vehicles) can only move along streets, prompting the need for a road model. Moreover, vehicles do not move independently of each other; they move according to well established vehicular traffic models, so the results for MANETs may not be directly applicable.

When dealing with vehicular mobility modeling, some authors [FHFB07] have distinguished between macro-mobility and micro-mobility. In some works authors go beyond that classification, including the sub-microscopic level. Figure 4.1 shows the different simulation granularities.

When considering macro-mobility, we not only take into account the road topology, but also the road structure (unidirectional or bidirectional, single- or multi-lane), the road characteristics (speed limits, vehicle-class based restrictions) and the presence of traffic signs (stop signs, traffic lights, etc.). Moreover, the concept of macro-mobility also includes the effects of the presence of points of interest, which influence movement patterns of vehicles on the road topology.

The concept of vehicular micro-mobility includes all aspects related to an individual car's speed and acceleration modeling. The micro-mobility description plays the main role in the generation of realistic vehicular movements, as it is responsible for effects such as smooth speed variation, cars queues, traffic jams and

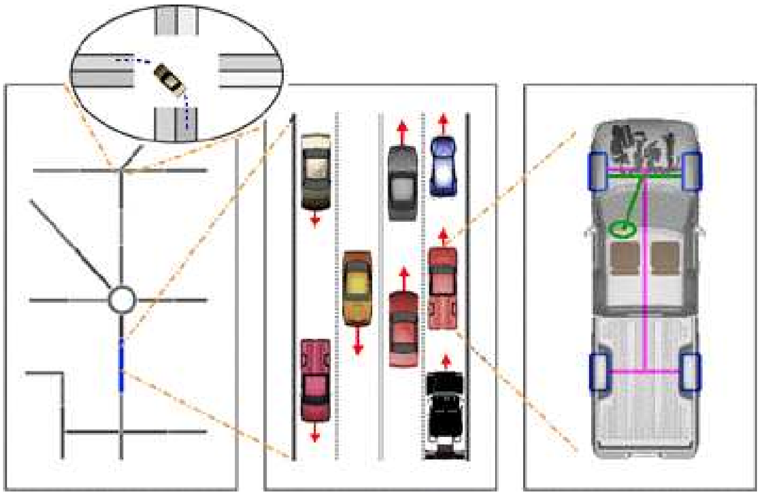


Figure 4.1: The different simulation granularities; from left to right: macroscopic, microscopic, sub-microscopic (within the circle: mesoscopic) [KR07].

overtakings. Three broad classes of micro-mobility models, featuring an increasing degree of detail, can be identified depending on whether the individual speed of vehicles is computed: (i) in a deterministic way, (ii) as a function of nearby vehicles behavior in a single lane scenario, or (iii) as a function of nearby vehicles behavior in a multi-flow interaction (i.e., urban) scenario.

Whereas it is crucial to test and evaluate protocol implementations in real testbed environments, logistic difficulties, economic issues and technology limitations make simulations the mean of choice in the validation of networking protocols for VANETs, and a widely adopted first step in development of real world technologies. A critical aspect in a simulation study of VANETs is the need for a mobility model reflecting the real behavior of vehicular traffic. Moreover, mobility models are required to be dynamically reconfigurable in order to reflect the effects of a particular communication protocol on vehicular traffic.

A wide variety of mobility models have been proposed for VANET simulations. Saha and Johnson [SJ04] modeled vehicular traffic with a random mobility of vehicles over real road topologies extracted from the maps of the US Census Bureau TIGER database. In that work, vehicles select one point over the graph as their destination and compute the shortest path to get there. The edges sequence is obtained weighting the cost of traveling on each road at its speed limit, and the traffic congestion.

Huang et al. [HHCW05] studied taxi behavior. They model the city as a Manhattan style grid with a uniform block size across the simulation area. All streets are assumed to be two-way, with one lane in each direction. Taxi movements are constrained by these lanes. A taxi is characterized by a preferred speed, a maximum acceleration and deceleration, a speed variation associated with the preferred speed at steady state, and a list of preferred destinations, i.e., the taxi stands. The taxis are randomly assigned one of three preferred speeds.

Choffnes et al. [CB05a] designed STRAW, a street mobility model that models real traffic conditions by incorporating a simple car-following model with traffic control to introduce vehicular congestion. STRAW relies on street plans to build a roadmap for the specified target region. It also provides at least one lane in each direction on which vehicles can move. To determine the initial positions of vehicles on the field, it uses a random street placement model that places a vehicle in a lane of a street just before an intersection. If another vehicle is already in that lane, the new vehicle is placed behind the existing one.

Haerri et al. [HFFB06b] proposed a vehicular mobility simulator for VANETs, called VanetMobiSim, which employs the Intelligent Driver Model (IDM) to determine the speed of vehicles.

Mahajan et al. [MPGW06] presented three different models: (i) *Stop Sign Model* (SSM), (ii) *Probabilistic Traffic Sign Model* (PTSM), and (iii) *Traffic Light Model* (TLM). The main difference between these models is basically the algorithm used to reproduce stop signs. All roads are modeled as bidirectional roads, the SSM and PTSM assume a single lane in each direction of every road, whereas TLM provides the option for modeling multiple lanes.

4.2.1 Factors Affecting Realistic Motion Patterns in VANETs

According to the concept map depicted in Figure 4.2, mobility models should include the following building blocks to generate realistic vehicular motion patterns [HFB09]:

- Accurate and realistic topological maps: street topologies should manage different densities of intersections, contain multiple lanes, different categories of streets and their associated speed limitations.

- Obstacles: obstacles should be understood in a wide sense, both as constraints to cars mobility and hurdles to wireless communications.

- Attraction/repulsion points: initial and final destinations of road trips are not random. Most of the time, drivers are moving to similar final destinations, called attraction points (e.g. office), or from similar initial locations, called repulsion points (e.g. home), a feature that creates bottlenecks.

- Vehicles characteristics: each category of vehicle has its own characteristics, which has an impact on a set of traffic parameters. For example, some urban streets and highways are forbidden to trucks depending on the time of the day. Moreover, acceleration, deceleration and speed capabilities of a car or a trucks are different. Accounting for these characteristics alters the traffic generation engine when modeling realistic vehicular motions.

- Trip motion: a trip is macroscopically seen as a set of source and destination points in the urban area. Different drivers may have diverse interests, which affect its trip selection.

- Path motion: a path is macroscopically seen as the set of road segments taken by a car on its trip between an initial and a destination point. As may also be observed in real life, drivers do not randomly choose the next heading when reaching an intersection, as it is currently the case in most vehicular networking traffic simulations. Instead, they choose their paths according to a set of constraints such as speed limitations, time of the day, road congestion, distance, and even the drivers' personal habits.

- Smooth deceleration and acceleration: vehicles do not abruptly break and accelerate. Models for decelerations and accelerations should consequently be considered.

- Human driving patterns: drivers interact with their environments, not only with respect to static obstacles, but also to dynamic obstacles, such as neighboring cars and pedestrians. Accordingly, the mobility model should control the mutual interactions between vehicles, such as overtaking, traffic jam, preferred paths.

- Intersection Management: It corresponds to the process of controlling an intersection, and may either be modeled as a static obstacle (stop signs), a conditional obstacle (yield sign), or a time-dependent obstacle (traffic lights). It is a key part in this framework that however only influences the Motion Constraint block, as the Traffic Generator block cannot see the difference between a stop sign or a high density traffic. Both are interpreted as a motion constraint.

- Time patterns: traffic density is not identical during the day. A heterogeneous traffic density is always observed at peak times, such as rush hours or during special events. This block influences the Motion Constrains and the Traffic Generator blocks, as it may alter the trip or path computation, and also the attraction/repulsion points.

- External Influence: some motion patterns cannot be proactively configured by vehicular mobility models as they are externally influenced. This category models the impact of accidents, temporary road works, or real-time knowledge of the traffic status on the motion constraints and the traffic generator blocks. Communication systems are the primary source of information about external influence.

The more building blocks a vehicular mobility model includes, the more realistic it is. Parameters defining the different major building blocks such as topological maps, car generation engine, or driver behavior engine cannot be randomly chosen but must reflect realistic configurations. Therefore, due to the large complexity to obtain such kind of information, the research community took more simplistic assumptions and neglected several blocks. As we will show throughout this chapter, most models available nowadays include a topological map, or at least a graph, as motion constraints. However, they do not include speed constraints or more generally attraction or repulsion points. The car generation engine block is also

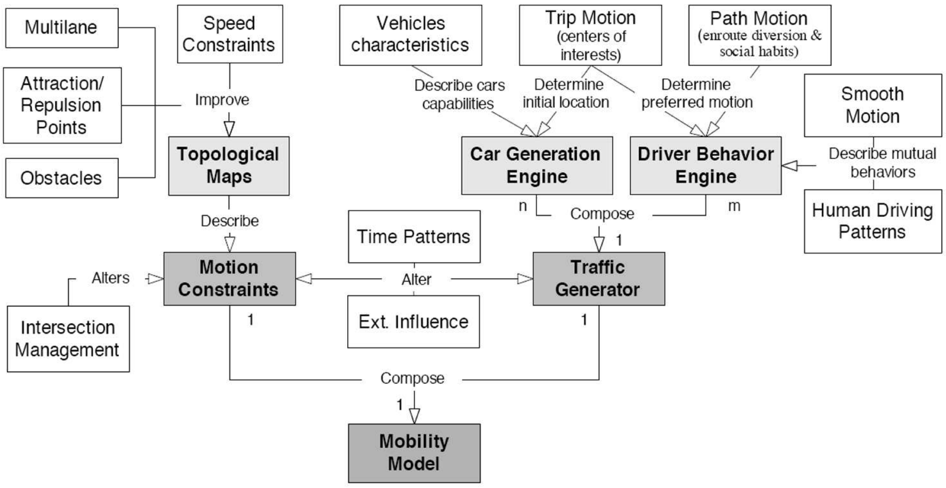


Figure 4.2: Concept map for the generation of realistic vehicular mobility models [HFB09].

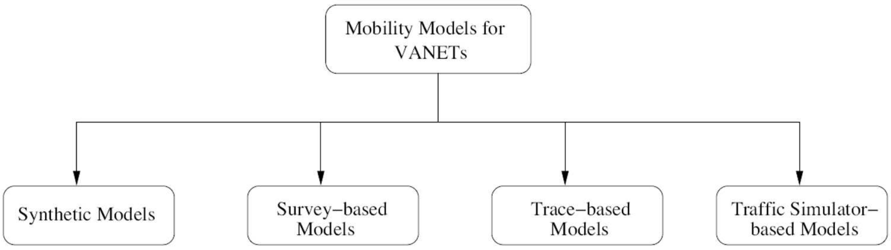


Figure 4.3: Classification of vehicular mobility models [HFB09].

widely absent from all models, and the driver behavior engine is limited to smooth accelerations or decelerations.

4.2.2 Mobility Models' Classification

Globally, the development of vehicular mobility models may be classified in four different classes [HFB09]: (i) Synthetic Models, wrapping all models based on mathematical models, (ii) Survey-based Models, extracting mobility patterns from surveys, (iii) Trace-based Models, generating mobility patterns from real mobility traces, and (iv) Traffic Simulators-based Models, where the vehicular mobility traces are extracted from a detailed traffic simulator. This classification is illustrated in Figure 4.3. In the next subsections, we explain each category in more detail.

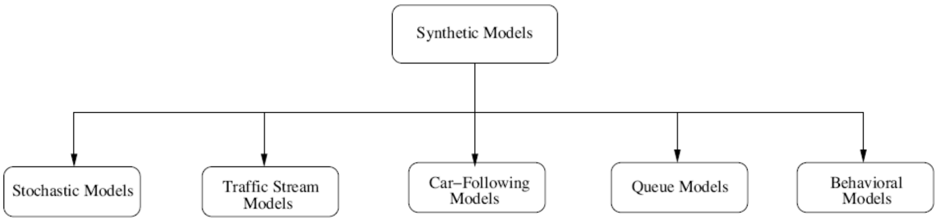


Figure 4.4: Classification of synthetic mobility Models [FHFB07].

4.2.2.1 Synthetic Models

The first and most well known class includes synthetic models. Major studies have been undertaken in order to develop mathematical models reflecting a realistic physical effect. Fiore [FHFB07] wrote a complete survey of models falling into this category.

According to Fiore's classification, Synthetic models may be separated into five classes: (i) Stochastic Models wrapping all models containing purely random motions, (ii) Traffic Stream models looking at vehicular mobility as hydrodynamic phenomenon, (iii) Car Following Models, where the behavior of each driver is modeled according to vehicles ahead, (iv) Queue Models, which model roads as FIFO queues and cars as clients, and (v) Behavioral Models, where each movement is determined by behavioral rules such as social influences. Figure 4.4 illustrates Fiore's classification. Next, we will show some examples of Synthetic Models.

Manhattan Model. The Manhattan mobility model [CBD02] is an Stochastic model which uses a grid road topology (see Figure 4.5b). The Manhattan model employs a probabilistic approach in the selection of node movements, since, at each intersection, a vehicle chooses to keep moving in the same direction with a 50% probability, and to turn left or right with a 25% probability in each case. Vehicles move over the grid with constant speed. The car interaction rules usually employed in the Manhattan model are too simple and do not reproduce a realistic driver behavior.

Fluid Traffic Motion. The Fluid Traffic Motion (FTM) [SMHW92] is a Traffic Stream model which accounts for the presence of nearby vehicles when calculating the speed of a car. This model describes car mobility on single lanes, but does not consider the case in which multiple vehicular flows have to interact, as in the presence of intersections.

The FTM describes the speed as a monotonically decreasing function of the vehicular density, forcing a lower bound on speed when the traffic congestion reaches a critical state by means of the following equation:

$$s = max\left[s_{min}, s_{max}\left(1 - \frac{k}{k_{jam}}\right)\right] \tag{4.1}$$

where s is the output speed, s_{min} and s_{max} are the minimum and maximum speed respectively, k_{jam} is the vehicular density for which a traffic jam is detected, and k is the current vehicular density of the road where the node is, whose speed is being computed, is moving on. This last parameter is given by $k = n/l$, where n is the number of cars on the road and l is the length of the road segment itself.

According to this model, cars traveling on very crowded and/or very short streets are forced to slow down, possibly to the minimum speed, if the vehicular density is found to be higher than or equal to the traffic jam density. On the other hand, as less congested and/or longer roads are encountered, the speed of cars is increased towards the maximum speed value. Thus, the Fluid Traffic Model describes traffic congestion scenarios, but still cannot recreate queuing situations, nor can it correctly manage car behavior in the presence of road intersections. Moreover, no acceleration is considered and it can happen that a very fast vehicle enters a short/congested edge, suddenly changing its speed to a very low value, which is definitely a very unrealistic situation.

Krauss Model. The Krauss Model [Kra98] falls into the Car Following Model subcategory. It takes four input variables (the maximum velocity υ_{max}, the maximum acceleration a, the maximum deceleration b, and the noise η that introduces stochastic behavior to the model), discretizes the time with step Δt, and is built up by the following set of equations:

$$\upsilon_i^{safe}(t+\Delta t) = \upsilon_{i+1}(t) + \frac{\Delta x_i(t) - \upsilon_{i+1}(t)\tau}{(\upsilon_i(t) + \upsilon_{i+1}(t))/2b + \tau} \tag{4.2}$$

$$\upsilon_i^{desired}(t+\Delta t) = min\left[\upsilon_{max}, \upsilon_i(t) + a\Delta t, \upsilon_i^{safe}(t+\Delta t)\right] \tag{4.3}$$

$$\upsilon_i(t+\Delta t) = max\left[0, \upsilon_i^{desired}(t+\Delta t) - \epsilon\, a\, \Delta t\, \eta\right] \tag{4.4}$$

Equation 4.2 computes the speed of vehicle i required to maintain a safety distance from its leading vehicle. The reaction time of the driver is represented by the time τ. Equation 4.3 determines the new desired speed for vehicle i, which is equal to the current speed plus the increment determined by the uniform acceleration, with upper bounds represented by the maximum and safe speeds. Equation 4.4 finally determines the speed of the following vehicle, by adding some randomness, in the measure of a maximum percentage ϵ of the highest achievable speed increment $a\Delta t$ (η is a random variable uniformly distributed in [0, 1]).

Intelligent Driver Model (IDM). Presented in Treiber et al. [THH00], such model characterizes drivers behavior depending on their front vehicle, thus falling into the so-called Car Following models category. The instantaneous acceleration of a vehicle is computed according to the following equations:

$$\frac{dv}{dt} = a\left[1 - \frac{v}{v_0}^{4} - \frac{s^*}{s}^{2}\right] \tag{4.5}$$

$$s^* = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{4.6}$$

In Equation 4.5, v is the current speed of the vehicle, v_0 is the desired velocity, s is the distance from preceding vehicle, and s^* is the so called desired dynamical distance. This last parameter is computed as shown in Equation 4.6, and is a function of the minimum bumper-to-bumper distance s_0, the minimum safe time headway T, the speed difference with respect to front vehicle velocity Δv, and the maximum acceleration and deceleration values a and b.

When combined, these formulae give the instantaneous acceleration of the car, divided into a "desired" acceleration $[v/v_0^4]$ on a free road, and braking decelerations induced by the preceding vehicle $[s^*/s^2]$. By smoothly varying the instantaneous acceleration, the IDM can realistically mimic car-to-car interactions on a single-lane and straight road. Interesting real world situations, such as queuing of vehicles behind a slow car, or speed reduction in presence of congested traffic can be reproduced. However, this model alone is not yet sufficient to obtain a realistic vehicular mobility model for urban environments.

Two different extensions were proposed to complete the model: (i) IDM with Intersection Management (IDM-IM), which adds intersection handling capabilities to the behavior of vehicles driven by the IDM, and (ii) IDM with Lane Changing (IDM-LC), which extends the IDM-IM model with the possibility for vehicles to change lane and overtake each others, taking advantage of the multi-lane capability of the macro-mobility description.

Queue Models. Queue models were introduced in the vehicular traffic field by Gawron [Gaw98]. According to the queue paradigm, each road is modeled as a FIFO queue, and each vehicle as a queue client. Each road queue k is characterized by its length l^k and a maximum flow q^k_{max}, determined by the number of lanes. Every time a vehicle enters a road, a travel time is computed, depending on the desired free flow speed of the driver v_{max}, on the number of vehicles on the road n^k and the road length.

The car is then enqueued in the priority queue of the road, according to the travel time calculated before. At every time step, vehicles whose travel time has expired can be removed from the head of the queue and inserted into the queue representing the next road in their trip. However, when multiple choices are available to exit a road, an intermediate step is necessary, and first-in-first-out queues are added for each outgoing flow. In that case, vehicles at the head of the priority queue are moved to one of the FIFO queues, depending on their destination.

The FIFO queues have a finite capacity, meaning that only a certain number of vehicles per second can access them. Since the movement from one road to another is constrained by the capacity of such next road, a vehicle at the head of an output queue can join the following queue only if there is space on the following road.

The capacity of a road is easily modeled as $c^k = \frac{n^k q^k_{max}}{x_{min}}$, where x_{min} is the distance between the front of two adjacent vehicles in jam conditions. Thus, if the new road has c^k cars already queued, it will not accept further vehicles, and drivers willing to enter the road will have to wait until a spot is freed.

It was shown [Gaw98] that even a simple expression of travel time l^k/v_{max}, which neglects the effect of vehicular density on the speed, leads to very good approximations of results obtained with much more complex microscopic mobility models.

Since queue models describe the movement of each vehicle in an independent way, but also with a minimal level of detail, they fall into an intermediate category with respect to macroscopic and microscopic descriptions, which can be referred to as mesoscopic. Queues models have very low computational cost, because they update the status of a vehicle only when a vehicle enters a new priority or FIFO queue. This allows to model very large road topologies, up to hundreds of thousands of vehicles. The drawback is the reduced realism of the outcome, which is less precise than that obtained with other models (e.g., queue models do not reproduce shockwaves caused by periodic perturbations, a common phenomenon in vehicular traffic).

Behavioral Models. Legendre et al. [LBDdAF06] introduced a novel approach to the problem of modeling human mobility, which can be applied to vehicular traffic as well. The approach was called behavioral modeling, and is borrowed from the fields of biological physics and artificial intelligence. The key idea is that every movement is determined by behavioral rules, which are imposed by social influences, rational decisions or actions following a stimulus-reaction process. These rules can be modeled as attractive or repulsive forces. In the case of vehicular mobility, the next intersection towards the trip destination wields an attractive force on the vehicle, whereas other vehicles or obstacles in general exert a repulsive force on it. The result from the composition of these forces determines the acceleration vector driving the car movement. This model is especially expensive under the computational point of view, as every movement requires the elaboration and composition of multiple inter-object forces.

4.2.2.2 Survey-based Models

Surveys are an important source of macroscopic mobility information. The major large scale surveys are provided by the US Department of Labor (DOL), which gathered extensive statistics of US workers' behaviors, spanning from the commuting time or lunch time, to traveling distance or preferred lunch types. By including such kind of statistics into a mobility model, one is able to develop a generic mobility model able to reproduce the pseudo-random or deterministic behavior observed in the real urban traffic.

Mobility simulators implementing survey-based models simulate arrival times at work, lunch time, breaks/errands, pedestrian dynamics (e.g., realistic speed-distance relationship and passing dynamics), and workday time-use such as meeting size, frequency, and duration. Vehicle traffic is derived from vehicle traffic data collected by state and local governments and models vehicle dynamics and diurnal street usage.

The UDel Mobility Model [UDe09] typically falls into survey-based models category. The mobility simulator is based on surveys from a number of research areas including: (i) time use studies performed by the US DOL, (ii) time use studies performed by the business research communities, or (iii) pedestrians and vehicle mobility studies performed by the urban planning and traffic engineering communities.

Another Survey-based model is the Agenda-based [ZHL06] mobility model, which combines both social activities and geographic movements. The movement of each node is based on an individual agenda, which includes all kinds of activities in a specific day. Data from the US National Household Travel Survey has been used to obtain activity distributions, occupation distributions and dwell time distributions.

A complex and computationally demanding vehicular mobility model was proposed by the ETH [ETH09], which generates public and private vehicular traffic over real regional roadmaps of Switzerland with a high level of realism within a period of 24 hours. The model is calibrated using data from census and other local or national mobility surveys or statistics.

The limitation of the survey-based approaches is that survey or statistical data are only able to provide a coarse grain mobility characterization, modeling global mobility patterns instead of precise movements. Yet, it has the advantage of being able to represent a particular mobility that would be too complex to model by mathematical equations. If we need a more detailed and realistic mobility representation, then we still require a complex synthetic model and we must calibrate it using surveys or statistics.

4.2.2.3 Trace-based Models

Due to the complexity of modeling vehicular mobility, only few very complex synthetic models are able to come close to a realistic modeling of motion patterns. A different approach could also be followed. Instead of developing complex models and then calibrating them using mobility traces or surveys, time could be saved by directly extracting generic mobility patterns from movement traces.

Such approach recently became increasingly popular as mobility traces started to be gathered through the various measurement campaigns launched by projects such as: (i) a project developed in conjunction with the German Fleetnet and the Network on Wheels projects [fle00, now08], which is based on traces measured by Daimler AG on a highway section, (ii) the UMAss DieselNet [UMa09] project, created by the University of Massachusetts, which provides mobility traces of a bus system in the city of Amherst, MA USA, and (iii) the Cabspotting project [Cab09] which equipped all taxi vehicles in the San Francisco Bay Area and provides a live visualization of the complete taxi system.

The most difficult part in this approach is to extrapolate patterns not observed directly by traces. By using complex mathematical models, it is possible to predict mobility patterns not reported in the traces to some extent. The limitation is also often linked to the class of the measurement campaign. For instance, if motion traces have been gathered for bus systems, an extrapolated model cannot be applied to the traffic of personal vehicles. Another limitation for the creation of trace-based vehicular mobility models is the limited availability of vehicular traces.

4.2.2.4 Traffic Simulators-based Models

By refining synthetic models and going through an intense validation process based on real traces or behavior surveys, some companies or research teams implemented realistic traffic simulators. Developed for urban traffic engineering, fine grain simulators such as PARAMICS [Par08], CORSIM [McT07], VISSIM [Vis08a], or SUMO [KR07], are able to model urban microscopic traffic, energy consumption, or even pollution or noise level monitoring. However, the output of these simulators cannot be used straightaway with network simulators, since no interface has been developed and so traces are mutually incompatible. In addition, some of these traffic simulators are commercial products and might require the purchase of a license.

The major drawback of this approach is the configuration complexity of these traffic simulators, as the calibration usually requires tweaking a large set of parameters. More important, the level of detail required for vehicular network simulators may not be as demanding as that for traffic analysis, since global vehicular mobility patterns and not the exact vehicular behaviors are by far sufficient in most cases. Finally, the purchase of a commercial license for the use of a commercial traffic simulator may even be waived, as some university programs offering a free of charge use of some commercial traffic simulators (VISSIM for instance) may be found.

4.2.3 Road Topology in Mobility Simulation

When considering macro-mobility we account for different characteristics such as the road topology, the road structure (unidirectional or bidirectional, single- or multilane), the road characteristics (speed limits, vehicle-class based restrictions) and the presence of traffic signs (stop signs, traffic lights, etc.). Moreover, the concept of macro-mobility also includes the effects of the presence of points of interest, which influence movement patterns of vehicles on the road topology. In this subsection we concentrate on the road topology.

The road topology is an important factor accounting for mobility in simulations, since the topology constrains cars' movements. Roughly described, an urban topology is a graph where vertices and edges represent, respectively, junction and road elements. Simulated road topologies can be generated ad hoc by users, randomly by applications, or obtained from real roadmap databases. Using complex layouts implies more computational time, but the results obtained are closer to real ones. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). These approaches are simple and it is easy to implement them in a simulator. When used, results can give some information about the general performance trends of the different algorithms studied. However, a more realistic layout should be used to ensure that the results are closer to reality. Layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the results obtained are likely to be similar in realistic environments.

User generated topologies are not realistic, and their use is not recommended. As proposed by [JBRAS03], another solution to randomly generate graphs on a particular simulation area is Voronoi tessellations. We therefore begin by distributing points over the simulation area, representing obstacles (e.g., buildings). Then, we draw the Voronoi domains, where the Voronoi edges represent roads and intersections running around obstacles. Accordingly, we obtain a planar graph representing a set of urban roads, intersections and obstacles.

Although being an interesting feature, these graphs lack realism too. Indeed, the distribution of obstacles should be fitted to match particular urban configurations. For instance, dense areas such as city centers have a larger number of obstacles, which in turn increases the number of Voronoi domains. By looking at topological maps, we can see that the density of obstacles is higher in the presence of points of interest. To address these issues, generating clusters of obstacles with different densities is required.

Figures 4.5a and 4.5b show synthetic topologies: (a) used defined, and (b) Manhattan-based, respectively. Figures 4.6a and 4.6b depict two random Voronoi maps: (a) with uniform density of streets, and (b) clustered density of streets. Finally, Figures 4.7a and 4.7b show two real roadmaps: (a) a map obtained from TIGER/line US database, and (b) a map obtained from openstreetmap.org.

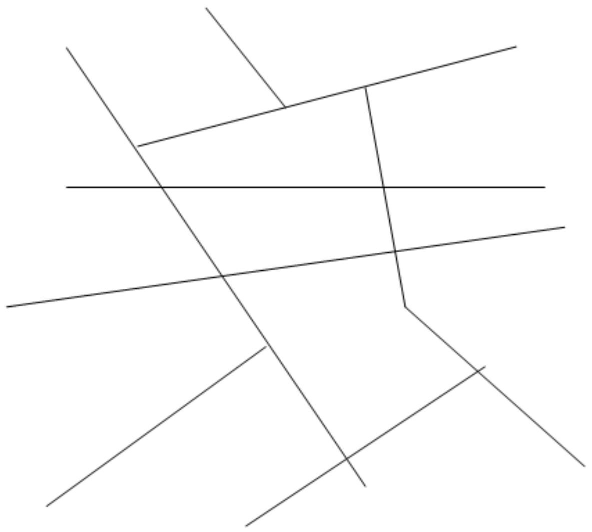
4.2.4 Validation of Mobility Models

The discussion on the generation of mobility models would not have been complete without addressing the issue of their validation. In the community, a misunderstanding exists about the word realistic. In many approaches, modelers assume that their synthetic mobility model is realistic because it uses behavioral models that are close to reality. For example, a model considering a microscopic interaction between cars is usually assumed to be more realistic than the Random Waypoint Model. However, it can not be directly assumed as realistic since the only method to assess the realism is by comparing the motion patterns with real topologies. This method is called Validation.

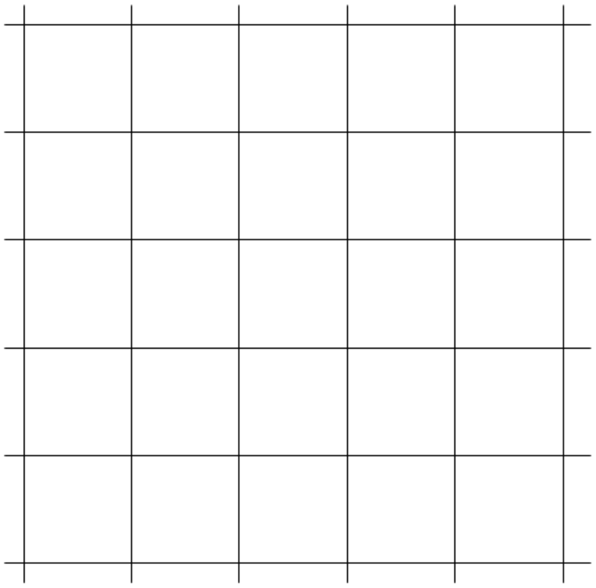
All commercial traffic simulators (CORSIM, VISSIM, etc.) and also some free mobility models (SUMO, SHIFT) have been validated based on real traces. Consequently, any mobility model based on these solutions could also be assumed to be valid.

Validating a mathematical model is an important step in order to guarantee its realism compared to real mobility patterns. One proposed solution is to gather mobility traces by large measurement campaigns, and then compare the patterns with those developed by the synthetic model.

A major limitation of most synthetic models comes from the complexity to model detailed human behaviors. Drivers are far from being machines and cannot be programmed to follow a specific behavior in all cases. Instead, they respond to stimuli and local perturbations that may have a global effect on traffic modeling. Accordingly, realistic mobility modeling should also consider behavioral theory.

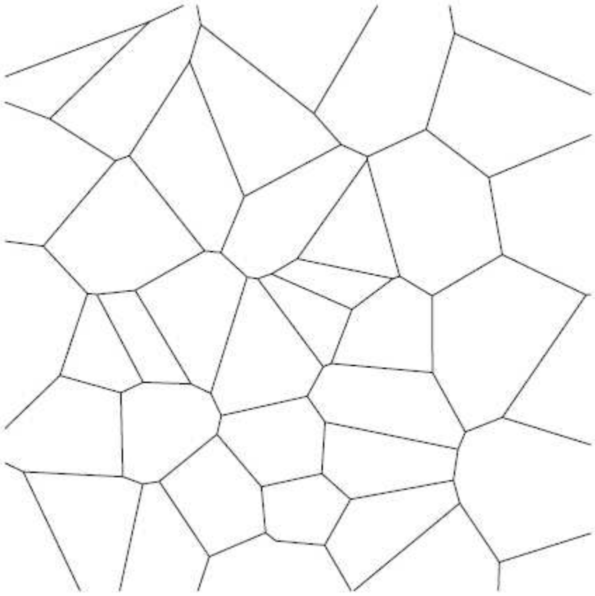


(a)

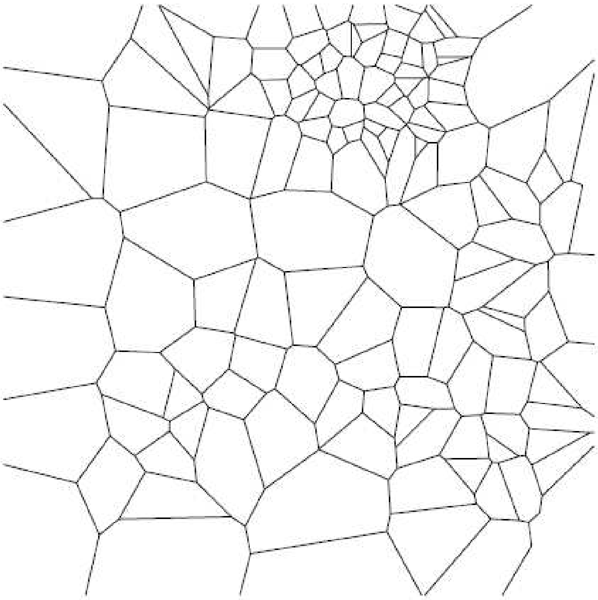


(b)

Figure 4.5: Examples of different roadmap topologies: (a) User defined, and (b) Manhattan.

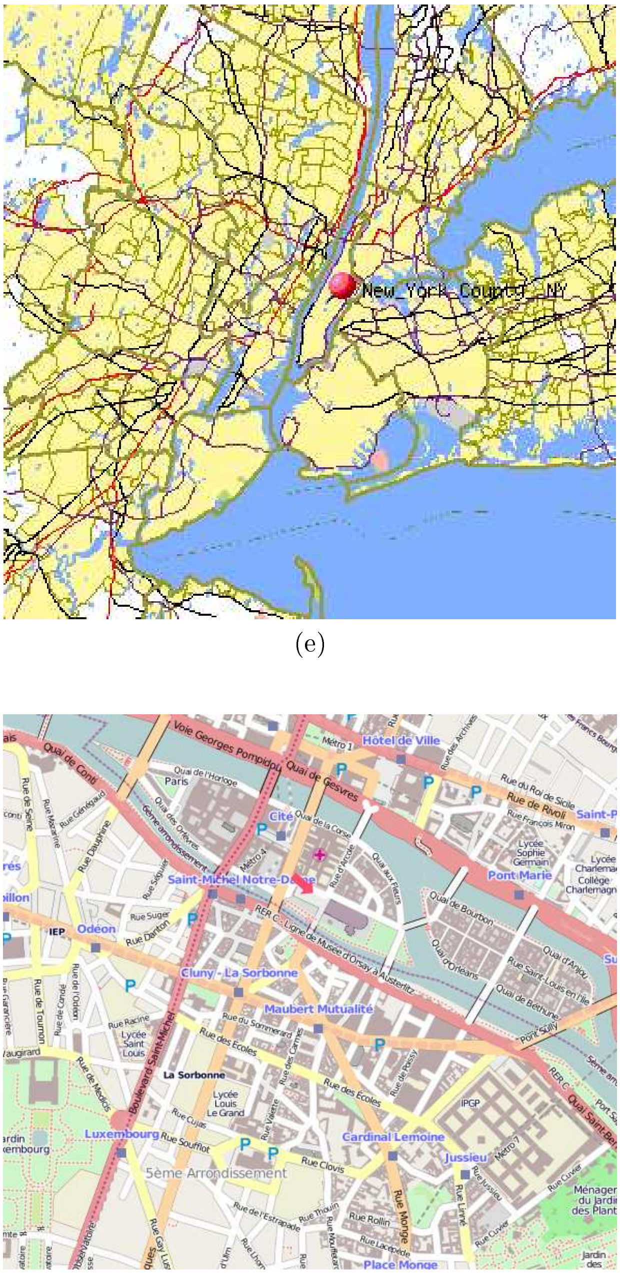


(c)



(d)

Figure 4.6: Examples of different roadmap topologies (cont.): (c) Voronoi uniform, and (d) Voronoi clustered.



(e)

(f)

Figure 4.7: Examples of different roadmap topologies (cont.): (e) TIGER database, and (f) openstreetmap.org.

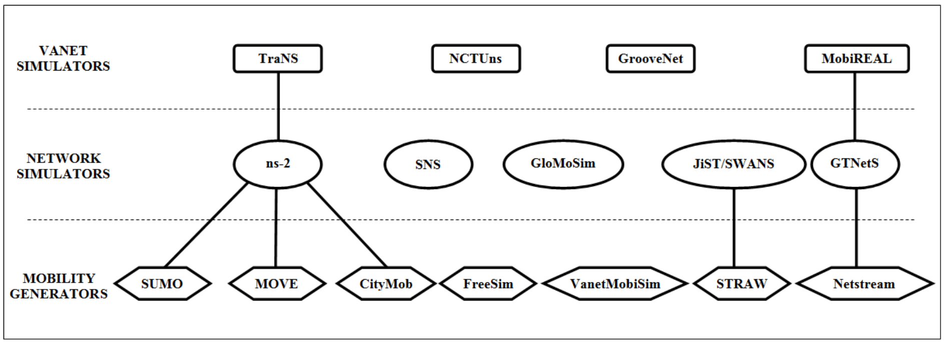


Figure 4.8: A taxonomy of VANET simulation software.

Although being related to human mobility, Musolesi et al. illustrated this approach [MM06] by developing a synthetic mobility model based on social network theory, and validated it using real traces. They showed that the model was a good approximation of human movement patterns.

4.3 Overview of VANET Simulators

In this section, we review various publicly available VANET simulators that are currently in use by the research community. In our study, we exclude proprietary VANET mobility generators or network simulators, such as TSIS-CORSIM [McT07], Paramics [Par08], Daimler-Chrysler Farsi and Videlio, Carisma [CEM03], VISSIM [Vis08a], QualNet [Sca06], or OPNET [OPN08]. We focus on freeware and open source tools that allow free access to the simulator source code.

Figure 4.8 presents the taxonomy of VANET simulation software. We have classified existing VANET simulation software into three different categories. They are: (a) vehicular mobility generators, (b) network simulators, and (c) VANET simulators.

Vehicular mobility generators are needed to increase the level of realism in VANET simulations. They generate realistic vehicular mobility traces to be used as an input for a network simulator. The inputs of the mobility generator include both the road model and the scenario parameters (i.e., maximum vehicular speed, vehicle arrival and departure rates, etc). The output of the trace details the location of each vehicle at every time instant for the entire simulation time. Examples are SUMO [KR07], MOVE[1] [mov07], CityMob [MCCM08b], STRAW [str08], FreeSim [Fre08], Netstream [MKT06] and VanetMobiSim [HFFB06a].

Network simulators perform detailed packet-level simulation of source, destinations, data traffic transmission, reception, background load, route, links, and channels. Examples are ns-2 [FV00], GloMoSim [Mar01], SNS [WS03], JiST/SWANS [swa04a], and GTNetS [GTN08]. Most existing network simulators are developed for *Mobile ad hoc Networks* (MANETs) and hence require VANET extensions (such

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[1] MOVE is used to convert SUMO traffic traces into ns-2 or GloMoSim compatible traces.

as using the vehicular mobility generators) before they can be used to simulate vehicular networks.

Finally, VANET simulators provide both traffic flow simulation and network simulation. Examples are TraNS [PRL$^+$07], NCTUns [nct08], GrooveNet [MWR$^+$06], and MobiREAL [mob08]. In the next few sections, we will discuss in greater depth the functions, and characteristics of vehicular mobility generators, network simulators, and VANET simulators.

4.3.1 VANET Mobility Generators

Vehicular mobility generators are needed to increase the level of realism in VANET simulations. In this section, we present the different vehicular traffic models, and the existing mobility generators.

4.3.1.1 Vehicular Traffic Models

Traffic modeling is a well-known research area in Civil Engineering, and it is crucial to correctly model vehicular traffic during the design phase of new roads and intersections [CB05b]. Transportation and traffic science classifies traffic models into macroscopic, mesoscopic, and microscopic models, according to the granularity with which traffic flows are examined. Macroscopic models, like METACOR [SCP$^+$94], model traffic at a large scale, treating traffic like a liquid applying hydrodynamic flow theory to vehicle behavior. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic models have considerably fewer demands on computer requirements than microscopic models. However, they do not have the ability to analyze transportation improvements in as much detail as the microscopic models.

Mesoscopic models, such as *Continuous Traffic Assignment Model* (CONTRAM) [Tay03], combine the properties of both microscopic and macroscopic simulation models. As in microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. However, their movements follow the approach of the macroscopic model, being governed by the average speed on the travel link, so movements do not consider individual dynamic vehicle speed and volume relationships.

Simulations of VANET scenarios are concerned with the accurate modeling of radio wave transmissions among nodes and, therefore, require exact positions of simulated nodes. Since both macroscopic and mesoscopic models cannot offer this level of detail, microscopic simulations, which model the behavior of single vehicles and the interactions between them, are the most appropriate mobility models for simulating VANETs. Transportation and traffic science has developed a number of microsimulation models, each taking a dedicated approach ranging from coarse to fine grain. Models that have been widely used within the traffic science community include the *Cellular Automaton* (CA) model [NS94], the *Stefan Krauss* (SK) model [Kra98], and the *Intelligent Driving Model* (IDM) [THH00]. Simulation time and memory requirements for microscopic models are high, usually limiting the network size and the number of simulation runs.

When dealing with vehicular mobility modeling, some authors [FHFB07] have distinguished between macro-mobility and micro-mobility. For macro-mobility, they refer to all the macroscopic aspects which influence vehicular traffic, i.e. the road topology, constrained car movements, the per-road speed limits, number of lanes, overtaking and safety rules for each street, or the traffic signs description establishing the intersections crossing rules. Micro-mobility refers instead to the drivers' individual behavior when interacting with other drivers or with the road infrastructure, i.e. traveling speed under different traffic conditions; acceleration, deceleration and overtaking criteria; behavior in the presence of road intersections and traffic signs, general driving attitude related to drivers' age, sex or mood, etc. It would be desirable for a trustworthy VANET simulation that both macro-mobility and micro-mobility descriptions are jointly considered when modeling vehicular movements.

4.3.1.2 Existing Mobility Generators

Nowadays, several simulation software environments exist and they are capable of generating trace files reflecting vehicles' movements.

- **VanetMobiSim** [HFFB06a] is an extension of the CANU Mobility Simulation Environment (CanuMobiSim) [CAN01] which focuses on vehicular mobility, and features realistic automotive motion models at both macroscopic and microscopic levels. At the macroscopic level, VanetMobiSim can import maps from the US Census Bureau *Topologically Integrated Geographic Encoding and Referencing* (TIGER) database, or randomly generate them using Voronoi tessellation. The TIGER/Line files constitute a digital database of geographic features, such as roads, railroads, rivers, lakes, and legal boundaries, covering the entire United States. VanetMobiSim adds support for multi-lane roads, separate directional flows, differentiated speed constraints and traffic signs at intersections. At the microscopic level, it supports mobility models such as Intelligent Driving Model with Intersection Management (IDM/IM), Intelligent Driving Model with Lane Changing (IDM/LC) and an overtaking model (MOBIL), which interacts with IDM/IM to manage lane changes and vehicle accelerations and decelerations, providing realistic car-to-car and car-to-infrastructure interactions. VanetMobiSim is based on JAVA and can generate movement traces in different formats, supporting different simulation or emulation tools for mobile networks including ns-2 [FV00], GloMoSim [Mar01], and QualNet [Sca06].
- **SUMO** (Simulation of Urban MObility) [KR07] 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., 10,000 streets, and it can import many network formats such as Visum [Vis08b], VISSIM [Vis08a], ArcView [Arc08], or XML-Descriptions. Thus, by combining SUMO and openstreetmap.org [ope08], we can simulate traffic in different locations of the globe. However, since SUMO is a pure traffic generator, its generated traces can not be

directly used by the available network simulators, which is a serious shortcoming.

- **MOVE** (MObility model generator for VEhicular networks) [mov07] rapidly generates realistic mobility models for VANET simulations. MOVE is built on top of SUMO. The output of MOVE is a mobility trace file that contains information of realistic vehicle movements which can be immediately used by popular network simulation tools such as ns-2 or GloMoSim. In addition, MOVE provides a GUI that allows the user to quickly generate realistic simulation scenarios without the hassle of writing simulation scripts as well as learning about the internal details of the simulator.

- **STRAW** (STreet RAndom Waypoint) [str08] provides accurate simulation results by using a vehicular mobility model on real US cities, based on the operation of real vehicular traffic. STRAW's current implementation is written for the JiST/SWANS discrete-event simulator, and its mobility traces can not be directly used by other network simulators, such as ns-2. STRAW is part of the C3 (Car-to-Car Cooperation) project [C302]. A more realistic mobility model with the appropriate level of detail for vehicular networks is critical for accurate network simulation. The STRAW mobility model constrains node movement to streets defined by map data for real US cities and limits their mobility according to vehicular congestion and simplified traffic control mechanisms.

- **FreeSim** [Fre08] is a fully-customizable macroscopic and microscopic free-flow traffic simulator that allows for multiple freeway systems to be easily represented and loaded into the simulator as a graph data structure with edge weights determined by the current speeds. Traffic and graph algorithms can be created and executed for the entire network or for individual vehicles or nodes, and the traffic data used by the simulator can be user generated or be converted from real-time data gathered by a transportation organization. Vehicles in FreeSim can communicate with the system monitoring the traffic on the freeways, which makes FreeSim ideal for ITS simulation. FreeSim is licensed under the GNU General Public License, and the source code is available freely for download.

Based on the limitations detected in the aforementioned mobility generators, in Chapter 6 we will present our proposals regarding VANET mobility simulation.

4.3.2 Network Simulators

Network simulators allow researchers to study how the network would behave under different conditions. Users can then customize the simulator to fulfill their specific analysis needs. Compared to the cost and time involved in setting up an entire testbed containing multiple networked computers, routers and data links, network simulators are relatively fast and inexpensive. Hence, they allow researchers to test scenarios that might be particularly difficult or expensive to emulate using real hardware, especially in VANETs. Network simulators are particularly useful to test new networking protocols or to propose modifications to existing ones in a controlled and reproducible manner.

4.3.2.1 Existing Network Simulators

Several network simulators can be used to simulate the communication between vehicles in *Inter-Vehicle Communication* (IVC) systems. Next we present the main characteristics of some of the most promising network tools to simulate VANET scenarios.

- **ns-2** [FV00] is a discrete event simulator developed by the VINT project research group at the University of California at Berkeley. The simulator was extended by the Monarch research group at Carnegie Mellon University [CMU01] to include: (a) node mobility, (b) a realistic physical layer with a radio propagation model, (c) radio network interfaces, and (d) the IEEE 802.11 *Medium Access Control* (MAC) protocol using the *Distributed Coordination Function* (DCF).

  However, the ns-2 distribution code had some significant shortcomings both in the overall architecture and the modeling details of the IEEE 802.11 MAC and PHY modules. In [CSEJ$^+$07], authors presented a completely revised architecture and design for these two modules. The resulting PHY is a full featured generic module capable of supporting any single channel frame based communications system. The key features include cumulative *Signal to Interference plus Noise Ratio* (SINR) computation, preamble and *Physical Layer Convergence Procedure* (PLCP) header processing and capture, and frame body capture. The MAC now accurately models the basic IEEE 802.11 *Carrier sense multiple access with collision avoidance* (CSMA/CA) mechanism, as required for credible simulation studies.

- **GloMoSim** [Mar01] is a scalable simulation environment for wireless and wired network. It has been designed using the parallel discrete-event simulation capability provided by Parsec [UCL08]. GloMoSim has been built using a layered approach similar to the OSI seven layer protocol model. Standard APIs are used between the different simulation layers. This allows the rapid integration of models developed at different layers by different people. The widely used QualNet [Sca06] simulator is a commercial version of GloMoSim.

- **JiST/SWANS** [swa04a]. JiST is a high performance discrete event simulation engine that runs over a standard Java virtual machine. It is a prototype of a new general purpose approach to building discrete event simulators, that unifies the traditional systems and language-based simulator designs. It outperforms existing highly optimized simulation engines both in time and memory consumption. Simulation code that runs on JiST need not be written in a domain-specific language invented specifically for writing simulations, nor must it be littered with special purpose system calls and "call backs" to support runtime simulation. Instead, JiST converts an existing virtual machine into a simulation platform, by embedding simulation time semantics at the byte-code level. Thus, JiST simulations are written in Java, compiled using a regular Java compiler, and run over a standard, unmodified virtual machine.

SWANS is a scalable wireless network simulator built on top of the JiST platform. It was created primarily because existing network simulation tools are not sufficient for current research needs. SWANS contains independent software components that can be composed to form a complete wireless or sensor network. Its capabilities are similar to the ones of ns-2 and GloMoSim, but SWANS is able to simulate much larger networks. SWANS leverages the JiST design to achieve higher simulation throughput, lower memory requirements, and run standard Java network applications over simulated networks. SWANS can simulate networks that are one or two orders of magnitude larger than what is possible with GloMoSim and ns-2, respectively, using the same amount of time and memory, and with a same level of detail [swa04b].

- **SNS** (a Staged Network Simulator) [WS03]. Traditional wireless network simulators are limited in speed and scale because they perform many redundant computations both within a single simulation run, as well as across multiple invocations of the simulator. The staged simulation technique [WS04] proposes to eliminate redundant computations through function caching and reuse. The central idea behind staging is to cache the results of expensive operations and reuse them whenever possible. SNS is a staged simulator based on ns-2. On a commonly used ad hoc network simulation setup with 1500 nodes, SNS executes approximately 50 times faster than regular ns-2 and 30% of this improvement is due to staging, and the rest to engineering. This level of performance enables SNS to simulate large networks. However, the current implementation is based on ns-2 version 2.1b9a, and it is not specifically designed to simulate VANET scenarios.

4.3.2.2 Comparison of Network Simulators

In Table 4.1, we present a summary of the studied network simulators and their characteristics. As shown, ns-2 is less suitable for simulating large networks but it is popular and easy to use, unlike SNS or JiST/SWANS. All the studied simulators provide open source code and are available freely on the Internet. Users can modify and enhance the code further, creating new versions. The major shortcoming is the lack of considerations for VANETs. For example, vehicular traffic flow models are not considered and 802.11p MAC is not included into the simulators (except for ns-2.33). Also, physical layer issues, obstacles, and road topologies present in a vehicular environment are often neglected.

4.3.3 VANET Simulators

One important aspect in a simulation model for an *Inter-Vehicle Communication* (IVC) system is the drivers' response to the IVC application. The reaction of drivers in different situations could affect traffic throughput [SK08]. For example, a driver who receives a collision warning message can either hit the brake or exit

Table 4.1: A comparison of the studied network simulators

		ns-2	GloMoSim	JiST/SWANS	SNS
Software	Portability	✓	✓	✓	✓
	Freeware	✓	✓	✓	✓
	Opensource	✓	✓	✓	✓
	Available examples	✓	✓	✓	✓
	Continuous development	✓	✗	✓	✗
	Large networks	✗	✓	✓	✓
	Console	✓	✓	✓	✓
	GUI	✓	✓	✓	✓
	Scalability	Poor	High	High	High
	Ease of setup	Easy	Moderate	Hard	Easy
	Ease of use	Hard	Hard	Hard	Hard
VANET	802.11p	Only for ns-2.33	✗	✗	✗
	Obstacles	✗	✗	✗	✗
	Vehicular traffic flow model	✗	✗	✗	✗

the highway, depending on the distance to the accident scene and the availability of exits.

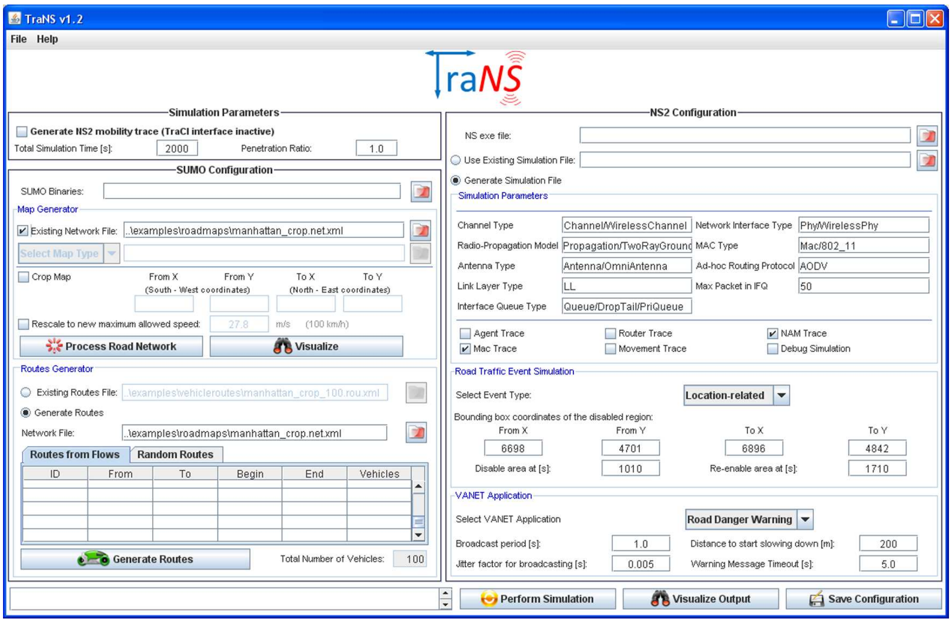
The software that allows one to change the behavior of vehicles (depending on a given application context) is known as an integrated framework or simply a VANET simulator.

4.3.3.1 Existing VANET Simulators

To the best of our knowledge, there are only a few integrated frameworks available. Currently, the mobility and network models in integrated frameworks are implemented as separated simulation tools. Therefore, there is a clear need for an integrated mobility and network simulator in order to evaluate the performance of IVC systems accurately. Below, we discuss these simulation frameworks.

- **TraNS** (Traffic and Network Simulation Environment) [PRL+07] is a simulation environment that integrates both a mobility generator and a network simulator, and it provides a tool to build realistic VANET simulations. TraNS provides a feedback between the vehicle behavior and the mobility model. For example, when a vehicle broadcasts information reporting an accident, some of the neighboring vehicles may slow down. TraNS is an open-source project providing an application-centric evaluation framework for VANETs.

  TraNS v1.2 has several features, including: (a) support for realistic 802.11p, (b) automated generation of road networks from TIGER and Shapefile maps, (c) automated generation of random vehicle routes, (d) mobility trace generation for ns-2, SUMO and ns-2 coupling through the TraCI [WPR+08] interface, and (e) possibility to simulate road traffic events, e.g., accidents.



☐ Generate NS2 mobility trace (TraCI interface inactive)
Total Simulation Time [s]: 2000
Penetration Ratio: 1.0
SUMO Binaries:
☑ Existing Network File: ..\examples\roadmaps\manhattan_crop.net.xml
☐ Crop Map
From X, From Y (South - West coordinates); To X, To Y (North - East coordinates)
☐ Rescale to new maximum allowed speed: 27.8 m/s (100 km/h)
○ Existing Routes File: ..\examples\vehicleroutes\manhattan_crop_100.rou.xml
● Generate Routes
Network File: ..\examples\roadmaps\manhattan_crop.net.xml

ID	From	To	Begin	End	Vehicles

Total Number of Vehicles: 100

NS exe file:
○ Use Existing Simulation File:
● Generate Simulation File
Channel Type: Channel/WirelessChannel
Network Interface Type: Phy/WirelessPhy
Radio-Propagation Model: Propagation/TwoRayGround
MAC Type: Mac/802_11
Antenna Type: Antenna/OmniAntenna
Ad-hoc Routing Protocol: AODV
Link Layer Type: LL
Max Packet in IFQ: 50
Interface Queue Type: Queue/DropTail/PriQueue
☐ Agent Trace ☐ Router Trace ☑ NAM Trace
☑ Mac Trace ☐ Movement Trace ☐ Debug Simulation

Select Event Type: Location-related
Bounding box coordinates of the disabled region:

From X	From Y	To X	To Y
6698	4701	6896	4842

Disable area at [s]: 1010
Re-enable area at [s]: 1710

Select VANET Application: Road Danger Warning
Broadcast period [s]: 1.0
Distance to start slowing down [m]: 200
Jitter factor for broadcasting [s]: 0.005
Warning Message Timeout [s]: 5.0

Figure 4.9: Graphical interface of TraNS.

Moreover, it provides two ready-to-use VANET applications: (a) Road Danger Warning (safety), and (b) Dynamic Reroute (traffic efficiency). TraNS can simulate large scale networks (tested up to 3000 vehicles), and allows for Google Earth visualization of simulations (currently works for TIGER files only).

- **GrooveNet** [MWR^{+}06] is a hybrid simulator which enables communication between simulated vehicles and real vehicles. By modeling Inter-Vehicular Communication within a real street map based topography, it eases protocol design and in-vehicle deployment. GrooveNet's modular architecture incorporates mobility, trip and message broadcast models over a variety of link and physical layer communication models. GrooveNet supports simulations of thousands of vehicles in any US city as well as the addition of new models for networking, security, applications, and vehicular interactions. It provides multiple network interfaces, and allows GPS and event-triggered (from the vehicles' on-board computer) simulations.

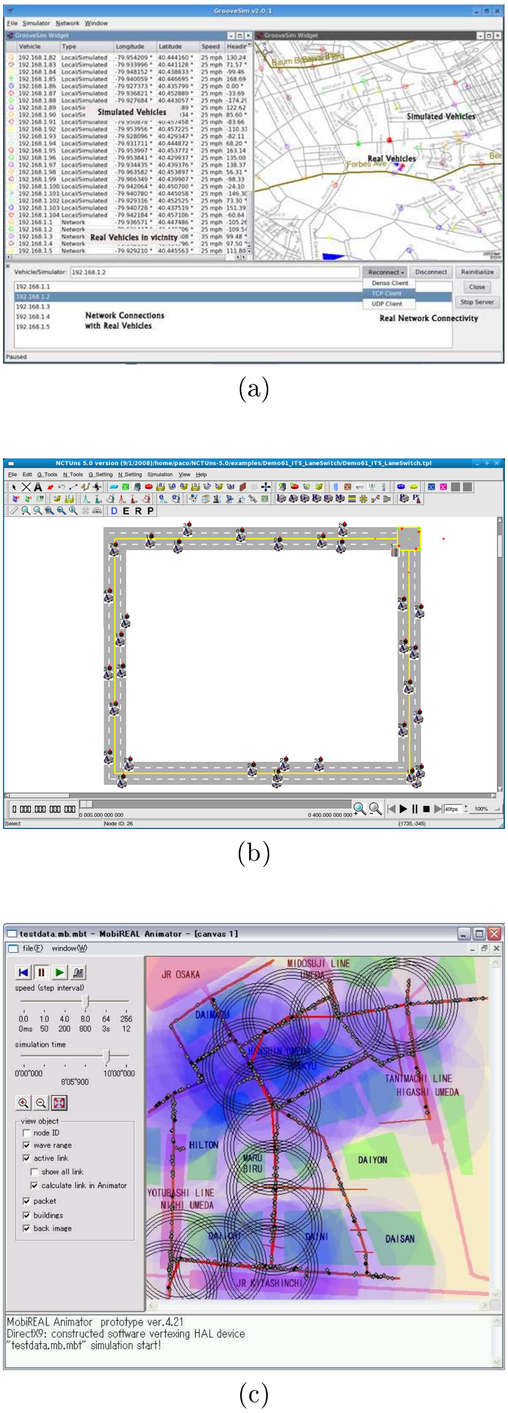
  GrooveNet supports three types of simulated nodes: (a) vehicles which are capable of multi-hopping data over one or more *Dedicated short-range communications* (DSRC) channels, (b) fixed infrastructure nodes, and (c) mobile gateways capable of *vehicle-to-vehicle* (V2V) and *vehicle-to-infrastructure* (V2I) communication. GrooveNet supports multiple message types such as GPS messages, which are broadcasted periodically to inform neighbors of a vehicle's current position, and vehicle emergency and warning event messages with priorities. Multiple rebroadcast policies have been implemented to investigate the broadcast storm problem. GrooveNet is able to support hybrid simulations where the simulated vehicle position, direction and messages are broadcasted over the cellular interface from one or more infrastructure nodes. Real vehicles communicate only with those simulated vehicles which are within its transmission range. GrooveNet generates street level maps for any place in the USA by importing TIGER files, which are available for free from the US Census Bureau. GrooveNet is based on the open-source ROADNAV [roa04] with significant additions, including a graph-based abstraction of streets, networking, simulation models, and a cross-platform GUI in Qt [Qt08].

- **NCTUns** (National Chiao Tung University Network Simulator) [nct08] is a high-fidelity and extensible network simulator and emulator capable of simulating various protocols used in both wired and wireless IP networks. Its core technology is based on a novel kernel re-entering methodology. Due to this novel methodology, NCTUns provides many unique advantages that cannot be easily achieved by traditional network simulators such as ns-2 and OPNET.

  NCTUns supports parallel simulations on multi-core machines. By using an innovative parallel simulation approach, it supports parallel simulations for fixed networks on multi-core machines. It also provides a highly-integrated and professional GUI environment that can help a user to quickly: (1) draw network topologies, (2) configure the protocol modules used inside a node, (3) specify the moving paths of mobile nodes, (4) plot network performance graphs, (5) play back the animation of a logged packet transfer trace, etc. All of these operations can be easily, intuitively, and quickly done with the GUI.

- **MobiREAL** [mob08] provides a new methodology to model and simulate realistic node mobility, and to evaluate MANET applications. It is a network simulator that can simulate realistic mobility of humans and vehicles, allowing to change their behavior depending on a given application context. MobiREAL can easily describe node mobility using C++. It adopts a probabilistic rule-based model to describe the behavior of mobile nodes, which is often used in cognitive modeling of human behavior. The proposed model allows one to describe how mobile nodes can change their destinations, routes and speeds/directions based on their positions, surroundings (obstacles and neighboring nodes), and information obtained from applications.

  MobiREAL simulates mobile ad-hoc networks by using the mobility support found in the Georgia Tech Network Simulator (GTNetS) [GTN08]. The MobiREAL Animator dynamically visualizes node movement, connectivity states, and packet transmission. This enhances the understanding of simulation results intuitively. Node mobility is simulated in the Behavior Simulator. Also, an algorithm for collision avoidance among pedestrians is implemented. Traffic congestion of vehicles can also be modeled.



Vehicle	Type	Longitude	Latitude	Speed	Headir
192.168.1.82	Local/Simulated	-79.954209 °	40.444160 °	25 mph	130.24
192.168.1.83	Local/Simulated	-79.933996 °	40.441128 °	25 mph	71.57 °
192.168.1.84	Local/Simulated	-79.948152 °	40.438833 °	25 mph	-99.46
192.168.1.85	Local/Simulated	-79.940059 °	40.446695 °	25 mph	168.69
192.168.1.86	Local/Simulated	-79.927373 °	40.435799 °	25 mph	0.00 °
192.168.1.87	Local/Simulated	-79.936821 °	40.452889 °	25 mph	-33.69
192.168.1.88	Local/Simulated	-79.927684 °	40.443057 °	25 mph	-174.2
192.168.1.89	Local/Sir	[illegible]	[illegible]	25 mph	122.62
192.168.1.90	Local/Sir	[illegible]	[illegible]	25 mph	85.60 °
192.168.1.91	Local/Simulated	-79.950878 °	40.457458 °	25 mph	-83.66
192.168.1.92	Local/Simulated	-79.953956 °	40.457225 °	25 mph	-110.31
192.168.1.93	Local/Simulated	-79.928096 °	40.429347 °	25 mph	-82.11
192.168.1.94	Local/Simulated	-79.931711 °	40.444872 °	25 mph	68.20 °
192.168.1.95	Local/Simulated	-79.953997 °	40.453772 °	25 mph	163.14
192.168.1.96	Local/Simulated	-79.953841 °	40.429937 °	25 mph	135.00
192.168.1.97	Local/Simulated	-79.934435 °	40.439376 °	25 mph	138.37
192.168.1.98	Local/Simulated	-79.963582 °	40.453897 °	25 mph	56.31 °
192.168.1.99	Local/Simulated	-79.966349 °	40.439907 °	25 mph	-98.33
192.168.1.100	Local/Simulated	-79.942064 °	40.450700 °	25 mph	-24.10
192.168.1.101	Local/Simulated	-79.940780 °	40.445058 °	25 mph	-146.3
192.168.1.102	Local/Simulated	-79.929336 °	40.452525 °	25 mph	73.30 °
192.168.1.103	Local/Simulated	-79.940728 °	40.437519 °	25 mph	151.39
192.168.1.104	Local/Simulated	-79.942184 °	40.457106 °	25 mph	-60.64
192.168.1.1	Network	-79.936571 °	40.447486 °	25 mph	-105.2
192.168.1.2	Network	[illegible]	[illegible]	25 mph	-109.5
192.168.1.3	Network	[illegible]	[illegible]	35 mph	99.48 °
192.168.1.4	Network	[illegible]	[illegible]	25 mph	97.50 °
192.168.1.5	Network	-79.929210 °	40.445563 °	25 mph	111.80

Vehicle/Simulator: 192.168.1.2

192.168.1.1
192.168.1.2
192.168.1.3
192.168.1.4
192.168.1.5

(a)

NCTUns 5.0 version (9/1/2008)/home/paco/NCTUns-5.0/examples/Demo61_ITS_LaneSwitch/Demo61_ITS_LaneSwitch.tpl

(b)

MobiREAL Animator prototype ver.4.21
DirectX9: constructed software vertexing HAL device
"testdata.mb.mbt" simulation start!

(c)

Figure 4.10: Graphical User Interfaces (GUIs) of (a) GrooveNet, (b) NCTUns, and (c) MobiREAL.

4.3.3.2 Comparison of VANET Simulators

In Table 4.2, we present a comparison of the studied VANET simulators. As shown, TraNS uses SUMO and ns-2, while MobiREAL uses GTNetS as the underlying network simulator. All simulators support different mobility models and provide microscopic traffic simulation. NCTUns provides random speed models, while the others model street speed instead. Currently, all simulators support trip and intersection models. So far, only TraNS and NCTUns have an implementation of 802.11p, and only GrooveNet and TraNS provide built-in VANET applications. In terms of ease of setup, NCTUns is considered the hardest one. In terms of ease of use, TraNS and GrooveNet are preferred.

Since these simulators were developed with different focus, results obtained when simulating similar VANET scenarios can differ greatly. TraNS and GrooveNet were developed to simulate VANETs. NCTUns was created for more general network simulation purposes, while MobiREAL was designed for simulating MANETs. MobiREAL was recently enhanced to support VANET simulation.

Table 4.3 presents a comparison of the *Graphical User Interfaces* (GUIs) provided by the studied VANET simulators. All simulators provide both alphanumeric and configuration file input, and console message output; nevertheless, the user interface for TraNS appears more sophisticated than the others. A lot of manual parameter inputs are needed for TraNS. All simulators provide street-level topology view. So far, only TraNS can support visualization using Google Earth.

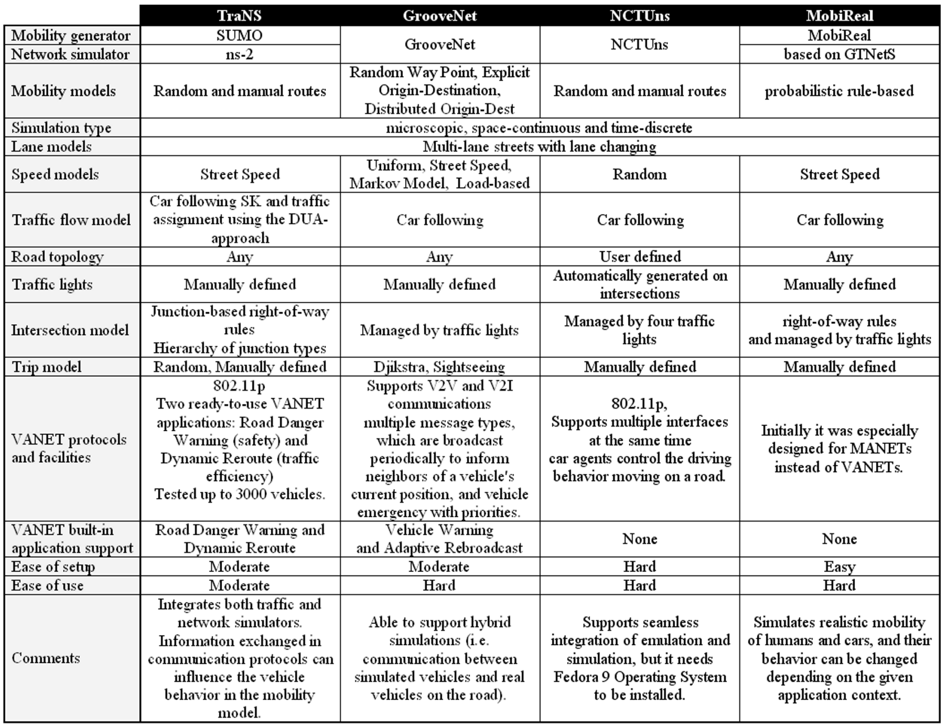
Finally, Table 4.4 presents a comparison on the popularity of the studied VANET simulators. To obtain the popularity results, we used the IEEE Xplore [IEE08], and the Google Scholar [goo08] tools to extract papers published from the year 2000 to 2010. We only considered papers that utilized the studied VANET simulators in their research. As shown, the currently two most popular VANET simulators are GrooveNet and NCTUns, although the use of these simulators in VANET research is far from being as usual as the use of general purpose network simulators, such as ns-2.

4.4 Radio Propagation Models

Two other important aspects in VANETs are the loss of power density experienced by wireless signals as they propagate through a specific environment, and the signal absorption due to some obstacles in the environment. When simulating radio signal transmission, a mathematical formulation of the radio wave propagation is usually defined as a function of parameters such as distance between vehicles, and radio frequency. This formulation is called *Radio Propagation Model* (RPM).

To estimate the impact of signal attenuation on packet losses we have two alternatives: (i) to use a very detailed analytical model that relates signal strength and noise at the receiver with *Bit Error Rate* (BER) and *Packet Error Rate* (PER), and (ii) to directly relate the BER or PER to distance under specific channel conditions. The latter, though more restrictive, allows us to simplify calculations and thus, it significantly reduces simulation run-time. Hence, we call Attenuation Schemes to the mathematical functions which determine the strength of the

Table 4.2: A comparison of the studied VANET simulators



	TraNS	GrooveNet	NCTUns	MobiReal
Mobility generator	SUMO	GrooveNet	NCTUns	MobiReal
Network simulator	ns-2			based on GTNetS
Mobility models	Random and manual routes	Random Way Point, Explicit Origin-Destination, Distributed Origin-Dest	Random and manual routes	probabilistic rule-based
Simulation type	microscopic, space-continuous and time-discrete			
Lane models	Multi-lane streets with lane changing			
Speed models	Street Speed	Uniform, Street Speed, Markov Model, Load-based	Random	Street Speed
Traffic flow model	Car following SK and traffic assignment using the DUA-approach	Car following	Car following	Car following
Road topology	Any	Any	User defined	Any
Traffic lights	Manually defined	Manually defined	Automatically generated on intersections	Manually defined
Intersection model	Junction-based right-of-way rules Hierarchy of junction types	Managed by traffic lights	Managed by four traffic lights	right-of-way rules and managed by traffic lights
Trip model	Random, Manually defined	Djikstra, Sightseeing	Manually defined	Manually defined
VANET protocols and facilities	802.11p Two ready-to-use VANET applications: Road Danger Warning (safety) and Dynamic Reroute (traffic efficiency) Tested up to 3000 vehicles.	Supports V2V and V2I communications multiple message types, which are broadcast periodically to inform neighbors of a vehicle's current position, and vehicle emergency with priorities.	802.11p, Supports multiple interfaces at the same time car agents control the driving behavior moving on a road.	Initially it was especially designed for MANETs instead of VANETs.
VANET built-in application support	Road Danger Warning and Dynamic Reroute	Vehicle Warning and Adaptive Rebroadcast	None	None
Ease of setup	Moderate	Moderate	Hard	Easy
Ease of use	Moderate	Hard	Hard	Hard
Comments	Integrates both traffic and network simulators. Information exchanged in communication protocols can influence the vehicle behavior in the mobility model.	Able to support hybrid simulations (i.e. communication between simulated vehicles and real vehicles on the road).	Supports seamless integration of emulation and simulation, but it needs Fedora 9 Operating System to be installed.	Simulates realistic mobility of humans and cars, and their behavior can be changed depending on the given application context.

Table 4.3: A comparison of VANET GUIs

GUI	**User friendly**	**Topology view**	**Parameters input**	**Output**
TraNS	Good	Google Earth with Zoom ability without obstacles	Street Map file Mobility file Graphical input	ns-2 trace .kmz file (Google Earth)
GrooveNet	Good	Street view with Zoom ability without obstacles	Street Map file Simulation file Graphical input	Simulation file Animation view
NCTUns	Moderate	User defined with Zoom ability with obstacles	Topology file Graphical input	Simulation file Animation view
MobiREAL	Moderate	User defined with Zoom ability without obstacles	Street Map file Mobility models Density and routes file Graphical input	Trace file Animation view

Table 4.4: Popularity comparison. Data obtained on April 22, 2010

	TraNS	**GrooveNet**	**NCTUns**	**MobiREAL**
Number of published papers that use the simulator	2	10	16	2
Number of citations found on IEEE Xplore	7	9	15	0
Number of citations found on Google Scholar	28	44	51	24

received signal as a function of the distance between sender and receiver, and so determining whether a packet could be considered successfully received.

4.4.1 Existing Radio Propagation Models

In this section we present some existing RPMs: (i) Free Space, (ii) Two-Ray Ground, (iii) Ricean and Rayleigh Fading, (iv) Shadowing, (v) RPMO, (vi) Nakagami, and (vii) Mahajan et al.

4.4.1.1 Free Space

The Free Space propagation model assumes ideal propagation conditions where there is only one clear line-of-sight path between the transmitter and receiver. H. T. Friis presented the following equation to calculate the received signal power P_r in free space at a distance d from the transmitter:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{4.7}$$

where P_t is the transmitted signal power, and G_t and G_r are the antenna gains of the transmitter and the receiver, respectively. L ($L \geq 1$) is the system loss, and λ is the wavelength.

The free space model basically represents the communication range as a circle around the transmitter. If a receiver is within the circle, it receives all packets. Otherwise, it loses all packets.

4.4.1.2 Two-Ray Ground

A single line-of-sight path between two mobile nodes is seldom the only means of propagation. The Two-Ray Ground (TRG) reflection model considers both the direct path and a ground reflection path. This model gives more accurate prediction at a long distance than the Free Space model. The received power at distance d is predicted by Equation 4.8:

$$P_r(d) = \frac{P_t G_t G_r {h_t}^2 {h_r}^2}{d^4 L} \tag{4.8}$$

where h_t and h_r are the heights of the transmit and receive antennas respectively. Note that the original equation in [Rap96] assumes $L = 1$. To be consistent with the Free Space model, L is added here.

The above equation shows a faster power loss than Equation 4.7 as distance increases. However, The TRG model does not give a good result for a short distance due to the oscillation caused by the constructive and destructive combination of the two rays. Instead, the free space model is still used when d is small.

Therefore, a cross-over distance d_c is calculated in this model. When $d < d_c$, Equation 4.7 is used. When $d > d_c$, Equation 4.8 is used. At the cross-over distance, Equations 4.7 and 4.8 give the same result, so d_c can be calculated as follows:

$$d_c = \frac{(4\pi h_t h_r)}{\lambda} \tag{4.9}$$

4.4.1.3 Ricean and Rayleigh Fading

Ricean fading is a stochastic model for radio propagation anomaly caused by partial cancellation 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 line-of-sight signal, is much stronger than the others.

Rayleigh fading is the specialized model for stochastic fading when there is no line-of-sight signal, and is sometimes considered as a special case of the more generalized concept of Ricean fading.

Rayleigh fading is a statistical model for the effect of a propagation environment on a radio signal, such as that used by wireless devices. Rayleigh fading models assume that the magnitude of a signal that has passed through such a transmission medium (also called a communications channel) will vary randomly, or fade, according to a Rayleigh distribution - the radial component of the sum of two uncorrelated Gaussian random variables.

Rayleigh fading is viewed as a reasonable model for tropospheric and ionospheric signal propagation as well as the effect of heavily built-up urban environments on radio signals. This model is most applicable when there is no dominant propagation along a line-of-sight between the transmitter and receiver. If there is a dominant line-of-sight, Ricean fading may be more applicable.

Rayleigh fading is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver. The central limit theorem holds that, if there is sufficiently scatter, the channel impulse response will be well-modeled as a Gaussian process irrespective of the distribution of the individual components. If there is no dominant component to the scatter, then such a process will have zero mean and phase evenly distributed between 0 and 2π radians.

Calling this random variable R, it will have a probability density function:

$$p_R(r) = \frac{2r}{\Omega} e^{-r^2/\Omega},\ r \geq 0 \tag{4.10}$$

Table 4.5: Some typical values of path loss exponent β

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

where $\Omega = E(R^2)$.

Often, the gain and phase elements of a channel's distortion are conveniently represented as a complex number. In this case, Rayleigh fading is exhibited by the assumption that the real and imaginary parts of the response are modeled by independent and identically distributed zero-mean Gaussian processes so that the amplitude of the response is the sum of two such processes.

4.4.1.4 Shadowing

The Free Space model and the TRG model predict the received power as a deterministic function of 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 effects, 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 multi-path 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 close-in distance d_0 as a reference. $\overline{P_r(d)}$ is computed relative to $P_r(d_0)$ as follows:

$$\frac{P_r(d_0)}{\overline{P_r(d)}} = \left(\frac{d}{d_0}\right)^{\beta} \tag{4.11}$$

β is called the path loss exponent, and is usually empirically determined by field measurement. From Equation 4.7, we know that $\beta = 2$ for free space propagation. Table 4.5 gives some typical values of β. Larger values correspond to more obstructions and hence faster decrease in average received power as distance becomes larger. $P_r(d_0)$ can be computed from Equation 4.7.

The path loss is usually measured in dB. So from Equation 4.11 we have:

$$\left[\frac{\overline{P_r(d)}}{P_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) \tag{4.12}$$

The second part of the shadowing model reflects the variation of the received power at certain distance. It is a log-normal random variable, that is, it is of Gaus-

Table 4.6: Some typical values of shadowing deviation σ_{dB}

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

sian distribution if measured in dB. The overall shadowing model is represented by Equation 4.13:

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB} \tag{4.13}$$

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. Table 4.6 shows some typical values of σ_{dB}. Equation 4.13 is also known as a log-normal shadowing model.

The shadowing model extends the ideal circle model to a richer statistic model: nodes can only probabilistically communicate when near the edge of the communication range.

4.4.1.5 RPMO

Radio Propagation Model with Obstacles (RPMO) [MK06], is an improvement of the Two-Ray Ground (TRG) model, and it resembles a propagation model introduced by A. Jardosh et al. in [JBRAS03].

In their implementation, a simulation area can contain a set of obstacles $O = obs_1, ..., obs_m$ of whatever shape, that totally hinders signal propagation. This feature causes nodes to have a non-circular coverage range when they are close to a block. In such a case there is a cone shaped part of the normal circular coverage range, that is an area of dark. Specifically, a dark area is a surface where the radio signals cannot propagate due to the blocks obstruction. Obviously, dark areas vary while mobile entities move, and they can be multiple for each node, whenever a node is nearby to more than one block. Every potential receiving node r_i, located in any of the dark areas of another sending peer s, will not hear any radio signal sent from s.

The formula to calculate the signal strength in reception is reported in Equations 4.14. In particular, the equation is exactly the same as for the Two-Ray Ground when no obstacles prevent signal propagation, and it is zero otherwise (authors did not consider obstacles that partially block radio signals).

$$P_{r-RPMO} = \begin{cases} P_{r-TRG} & No\,obstruction \\ 0 & Else \end{cases} \tag{4.14}$$

4.4.1.6 Nakagami Model

As an addition to the existing radio propagation models, Nakagami RF model is developed and added in ns-2 v2.33. Nakagami is a mathematical general modeling of a radio channel with fading. Compared to other existing models (Shadowing and Two-Ray Ground), Nakagami RF model has more configurable parameters to allow a closer representation of the wireless communications channel. It is able to model from an perfect free space channel, to a moderate fading channel on a highway, even to a dramatically fading channel in urban scenarios.

The Nakagami distribution is defined by the following probability density function (pdf):

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} exp\left[-\frac{mx^2}{\Omega}\right],\ x \geq 0,\ \Omega > 0,\ m \geq 1/2 \tag{4.15}$$

The corresponding pdf of power (square of the signal amplitude) at a given distance can be obtained by a change of variables, and it is given by a gamma distribution of the following form:

$$p(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} exp\left[-\frac{mx}{\Omega}\right],\ x \geq 0 \tag{4.16}$$

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

Notice that the Rayleigh distribution is a special case of the Nakagami distribution where $m(d) = 1$ (for every d), and that larger values of m cause less severe fading.

4.4.1.7 Mahajan et al.

Physical obstacles also affect radio signal propagation through attenuation, reflection, diffraction, and refraction. This is in addition to the free-space attenuation of radio signals with distance. Since a receiver needs a minimum signal-to-noise ratio to receive data, accounting for the obstacles is important when evaluating VANETs through simulations.

Traditional analytical models have limitations in capturing complex real-world factors that influence radio signal strengths. The Mahajan et al. [MPGW07] approach uses empirically measured data from real urban settings to capture the impact of different factors on radio signals in a few simulation parameters.

They measured the signal strength variation from a commodity access point around two city blocks in downtown Tallahassee - including a 100m x 100m block with several three-story buildings and a 200m x 50m block with one-story buildings. They placed an 802.11b Linksys wireless access point at a corner of the block being measured. They then used the Wavemon [wav09] tool running on a Linux laptop equipped with a wireless PCI card to take signal strength measurements at various locations around the block.

The empirical data were composed of the distances from the access point and the associated signal strength. A logarithmic transformation was performed on collected distances before a linear regression was applied on the signal strength S (in decibels/milliwatts or dBm), as a function of distance d (in meters) [Jai91]. Logarithmic linear regressions yielded the following formulas, with R^2 (coefficient of determination) of 0.6836 and 0.9698, indicating that 68% and 97% of the variances in data are explained by these equations, respectively.

$$Block\,1 : S = -25.809 - 29.773 \cdot log(d) \tag{4.17}$$

$$Block\,2 : S = -20.089 - 33.012 \cdot log(d) \tag{4.18}$$

From the structure of Equations 4.17 and 4.18, they derived a simplified parametrization of the received signal strength.

$$P_r = P_t + A - B \cdot log(d) \tag{4.19}$$

P_r and P_t are the signal strengths (in dBm) at the receiver and the sender respectively; d is the distance between the two in meters, and A and B are tunable parameters.

The propagation models used in ns-2 (Free Space and Two-Ray Ground) can also be represented in the form of Equation 4.19. Equations 4.7 and 4.8 could be represented in the form of Equation 4.19, after converting watts into dBm. The default values of A and B in ns-2 for the Free Space model are $A = -31$ and $B = 20$, and for the TRG model: $A = 7.5$ and $B = 40$.

Assuming that the received signal strength largely depends on the presence of obstacles and the distance from the sender, we can interpret A and B as follows. Parameter A captures the constant factor reduction in signal strength due to the presence of obstacles in a particular terrain. Parameter B captures the order of magnitude reduction in the signal strength with the distance from sender, the order of magnitude being determined by nature of the obstacles. The actual values of A and B would be quite different for various urban settings, and even across different regions within a single urban setting.

4.4.2 Limitations of Existing Attenuation Schemes

As presented in Section 4.4.1, the ns-2 simulator [FV00] offers some RPMs to estimate the wireless signal strength. These models assume a flat surface, where the simulation environment contains no objects that could block the signal. The RPMs included in ns-2 v2.33 are: (i) Free Space model, (ii) Two-Ray Ground model that accounts for multipath reflection from the ground, (iii) Ricean and the Rayleigh fading models, that account for multipath propagation of the radio waves, (iv) Nakagami model that is a mathematical general modeling of a radio channel with configurable fading, and (v) Shadowing model which models more complex environments.

In ns-2, the provided RPMs simulate a network with total absence of obstacles. Only the power level is taken into account, i.e., when the first bit of a new packet arrives, the power level at which the packet was received is compared to two different values, i.e., the carrier sense threshold and the receive threshold. Hence, determining whether or not a packet reaches its destination is a deterministic process. In fact, only the Nakagami model uses a probabilistic distribution.

Table 4.7 compares five of the most representative RPMs provided by the ns-2 simulator, and two others proposed in [MK06] and [MPGW07]. When studying the results presented in [MK06], we realize that the simulation scenario is constrained to an orthogonal grid, which could not represent a typical European city where the streets' layout is usually irregular. Moreover, the communications range is limited to 250m, which, as we will later demonstrate, is too limiting for 802.11p based communications. In [MPGW07], the authors implemented different traffic lights, lane and stop models, but they did not measure notification time and they only simulated 100 nodes. Due to these limitations, in Chapter 7 we propose four different radio propagation models, specially designed to correctly simulate traffic safety applications for VANETs.

We understand that excessive details when modeling the physical layer may extend the simulation run-times with little or no impact on the results, while too few details invariably lead to inaccurate results. To achieve a trade-off between accuracy and run-time, propagation models must simplify and reduce the calculations involved.

4.4.3 Visibility Schemes

One relevant effect in radio propagation is the signal absorption due to some obstacles in the environment, i.e., buildings, geographic conditions such as mountains, etc. In our simulations we focus on urban scenarios, thus taking into account the low depth of penetration of the wireless signal into buildings and other urban artifacts. Simulation results will largely depend on how this effect is modeled.

The simplest approach concerning visibility is not considering obstacles at all, as if vehicles were moving in an empty surface. This is the default model implemented within the ns-2 simulator. Its major drawback is that it will cause the obtained results to be very optimistic, as we always consider that vehicles are in line-of-sight. A variation of this scheme is reducing the scenario to a simple highway where all the vehicles move in the same direction, like the one found in [SPC09] and [BSKW08].

A more complex scheme, used in [MCCM08b] and [MK06], assumes that all the vehicles are moving only in streets arranged as a Manhattan-style grid, so that vehicle movements can only be vertical or horizontal. This environment is more realistic than the previous one, but in real scenarios (like many European cities) it is very difficult to find perfect Manhattan layouts. In a Manhattan-style visibility scheme, two vehicles in different streets are in line-of-sight (see Figure 4.11) when the following condition is satisfied:

Table 4.7: Some existing RPMs for VANETs

Schemes	**Remarks**
Free Space	The received power is only dependent on the transmitted power, the antenna gains and on the distance between the sender and the receiver. Obstacles are not modeled.
Two-Ray Ground	Assumes that the received energy is the sum of the direct line-of-sight path and the reflected path from the ground. It takes no account for obstacles and sender and receiver have to be on the same plane.
Ricean and Rayleigh fading	Both models describe the time-correlation of the received signal power. Ricean model considers indirect paths between the sender and the receiver, while Rayleigh fading model considers when there is one dominant path and multiple indirect signals.
Nakagami	Signal reception power is determined using a probability distribution dependant on the distance. Configuration parameters are used to simulate different levels of fading. It can be interpreted as a generalization of the Rayleigh distribution.
Shadowing	A gaussian random variable is added to the path loss to account for environmental influences.
RPMO [MK06]	Radio Propagation Model with Obstacles models obstacles, but when there are no obstacles, RPMO behaves like Two-ray Ground, so distance attenuation is not taken into account.
Mahajan et al. [MPGW07]	This model behaves like Two-ray Ground, adding the influence of obstacles and the distance attenuation, but it has been designed considering the signal propagation under the 802.11b technology.

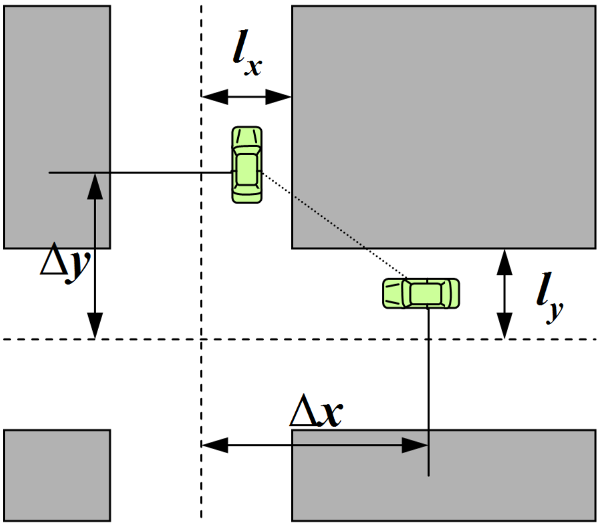


Figure 4.11: Parameters to determine if two vehicles are in line-of-sight in a Manhattan layout.

$$(\Delta x < l_x) \vee (\Delta y < l_y) \vee \left(\frac{-\Delta y \times l_x}{\Delta x} + \Delta y < l_y \right), \tag{4.20}$$

where Δx is the absolute difference between the x coordinates of the two vehicles ($\Delta x = |x_1 - x_2|$), Δy is the absolute difference between the y coordinates of the two vehicles ($\Delta y = |y_1 - y_2|$), l_x is the half of the streets' width in the x coordinate, and l_y is the half of the streets' width in the y coordinate. This approach is simple and easy to implement in a simulator, and it provides information about the general trends of the different algorithms. However, a more realistic layout should be used to ensure that the obtained results are closer to reality.

4.4.3.1 Visibility Scheme for Real Maps

We now propose a more realistic visibility scheme which has been designed to be used in real scenarios where streets are not required to be arranged orthogonally and, therefore, they can represent a realistic layout. Figure 4.12 shows the mathematical basis of the visibility model proposed for real scenarios. Since two vehicles in the same street are considered to be in line-of-sight, we will now focus on vehicles located in different streets.

The values we know *a priori* are the coordinates of vehicle A (x_A, y_A), the coordinates of vehicle B (x_B, y_B), the angle (α) formed by the streets where the two vehicles are moving, and the coordinates of the vertex V (x_V, y_V) the two streets have in common. As we can see, vehicles A and B are in line-of-sight if the following condition is satisfied:

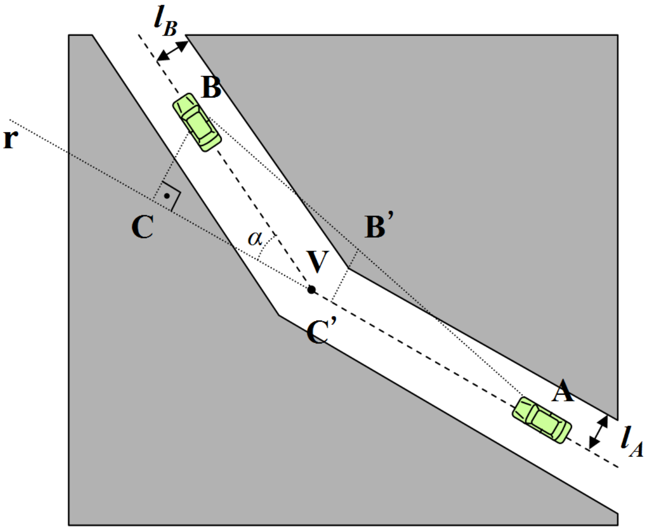


Figure 4.12: Parameters to determine if two nodes are in line-of-sight in a realistic layout.

$$d(B', C') < l_A \tag{4.21}$$

Function d represents the Euclidean distance between two points, and l_A is half the width of the street where vehicle A is located. We can find the value of $d(B', C')$ as follows:

$$\frac{d(B,C)}{d(A,C)} = \frac{d(B',C')}{d(A,C')} \Rightarrow d(B',C') = \frac{d(A,C') \cdot d(B,C)}{d(A,C)} \tag{4.22}$$

The three terms on the right hand of the equality can be computed using the known values. Point C' depends on l_A, l_B, α and the vertex coordinates (V) which the two streets have in common. Figure 4.13 graphically depicts the different points and distances used in computations. The value of $d(A, C')$ can be calculated as follows:

$$d(A,C') = d(A,V) - d(C',V) = d(A,V) - \left(\frac{l_B}{\sin\alpha} - \frac{l_A}{\tan\alpha}\right) \tag{4.23}$$

Distance between points B and C is equal to the minimum distance (d_{min}) between point B (x_B, y_B) and the line r (formed as an extension of the street where A is located) in the form $A_r \cdot x + B_r \cdot y + C_r = 0$. The values of A_r, B_r and C_r for a street defined as a straight line passing through an initial point (x_0, y_0) and a final point (x_1, y_1) are computed using the following expressions:

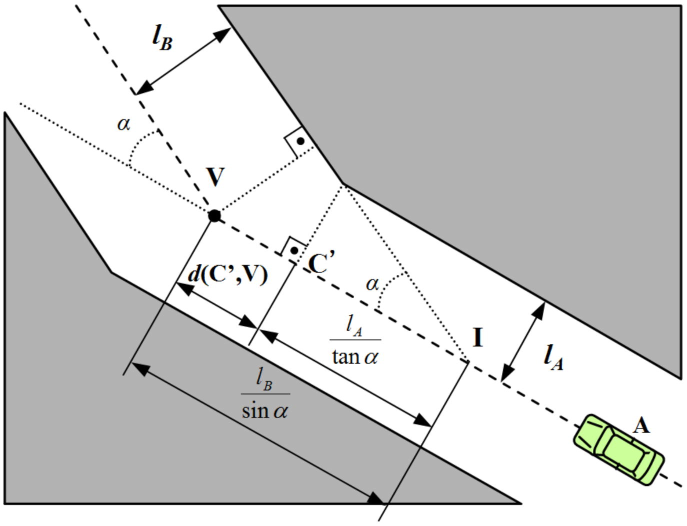


Figure 4.13: Graphical explanation of the computation of $d(C', V)$.

$$\begin{aligned} A_r &= y_1 - y_0 \\ B_r &= -x_1 + x_0 \\ C_r &= y_0 \cdot (x_1 - x_0) - x_0 \cdot (y_1 - y_0) \end{aligned} \tag{4.24}$$

Once obtained the general equation of the line, $d(B, C)$ can be calculated as follows:

$$d(B, C) = d_{min}(B, r) = \frac{|A_r \cdot x_B + B_r \cdot y_B + C_r|}{\sqrt{A_r^2 + B_r^2}} \tag{4.25}$$

Finally, $d(A, C)$ has the following value:

$$d(A, C) = d(A, V) + d(V, C) = d(A, V) + \frac{d(B, C)}{\tan\alpha} \tag{4.26}$$

Although these results represent a detailed geometrical study of visibility, they involve plenty of calculations just to determine if a pair of vehicles are in line-of-sight. In a real simulation, this situation must be checked every time sender or receiver change their positions, leading to excessive simulation times. Hence, in our simulations, we use a simplified approach to visibility that provides a relevant degree of realism without extending our simulation times considerably. For that purpose we will use the angle between two streets to determine whether two vehicles located in those streets are capable of communicating, or if the signal is blocked by the buildings (see Section 7.2.4.2).

4.5 Methodology and Metrics

Simulation results presented in this thesis were obtained using the ns-2 simulator [FV00]. We modified the simulator to follow the upcoming WAVE standard closely[2], extending the ns-2 simulator to implement IEEE 802.11p. We chose the IEEE 802.11p technology because it is expected to be widely adopted by the industry.

In terms of the physical layer, the data rate used for packet broadcasting was fixed at 6 Mbit/s, i.e., the default rate for broadcasting in 802.11p when assuming a 20 MHz channel. The MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA), and *Quality of Service* (QoS) extensions. Therefore, application messages are categorized into different *Access Categories* (ACs), where AC0 has the lowest, and AC3 the highest priority. The contention parameters used for the *Control Channel* (CCH) are shown in [Eic07]. Thus, in our warning message dissemination mechanism, warning messages have the highest priority (AC3) at the MAC layer, while *beacons* have lower priority (AC1).

Each simulation lasted for 450 seconds. In order to achieve a stable state before gathering data traffic, we only started to collect data after the first 60 seconds. Since in this thesis we concentrate on VANET safety applications, we evaluated the following performance metrics: (i) the percentage of blind vehicles, (ii) the number of packets received per vehicle, and (iii) the warning notification time. The percentage of blind vehicles is the percentage of vehicles that does not receive the warning messages sent by the warning mode vehicles. These vehicles can remain blind because of their positions, due to collisions, or due to signal propagation limitations. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle.

Since the *Random Waypoint* (RWP) mobility model is considered unrealistic [YLN03], in our experiments vehicles move according to a mobility model that we developed, called *Downtown Model* (DM) [MCCM08b]. DM is a model included in the CityMob mobility generator (see Section 6.2.1) that we propose and validate for use in VANETs. In this model, streets are arranged in a Manhattan style grid, with a uniform block size across the simulation area. Vehicles will move with a random speed, lower than speed limits. Figure 4.14 shows the simulated urban topology. Dark vehicles are damaged vehicles which send warning messages.

Our model also simulates traffic lights with different delays. When a vehicle meets a red traffic light, it comes to a stop until the traffic light turns to green. Moreover, our model adds traffic density behavior similar to a real town, where traffic is not uniformly distributed. Hence, there will be zones with a higher vehicle density. These zones are usually in the downtown, and vehicles must move more slowly than those in the outskirts. CityMob[3] has also the following capabilities: (i) multiple lanes in both directions for every street, (ii) vehicle queues due to traffic jams, and (iii) the possibility of having more than one downtown.

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[2] All these improvements and modifications of the simulator are publicly available at http://www.grc.upv.es/software/

[3] Available at http://www.grc.upv.es/software/

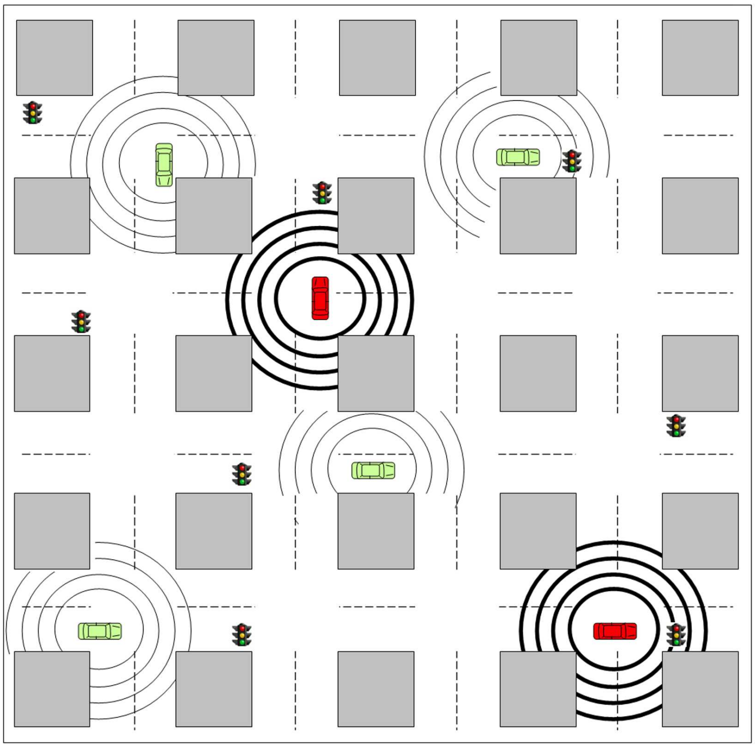

Figure 4.14: Simulated topology.

4.6 Summary

The increasing popularity and attention in VANETs has prompted researchers to develop accurate and realistic simulation tools. In this chapter, we introduced some of the different available mobility models for VANETs which reproduce the complex vehicular motion patterns, presented a classification of them, and discussed some important concepts related with mobility such as the road topology and the mobility models' validation. As shown, different solutions were proposed, from mathematical to behavioral models. The choice between the different approaches highly depends on the application requirements. For example, if the application is a vehicular safety protocol, the mobility model must represent the real motion at a high level of precision, and thus must be generated by a synthetic model. In contrast, when testing a data dissemination protocol, the gross motion patterns are sufficient and a trace or survey-based model may therefore be envisioned.

We also made a survey of several publicly available mobility generators, network simulators, and VANET simulators. While each of the studied simulators provides a good simulation environment for VANETs, refinements and further contributions are needed before they can be widely used by the research community.

In addition, we showed the existing Radio Propagation Models, evidencing their limitations, specially in the attenuation and visibility proposed schemes. The aforementioned limitations motivated our proposals regarding mobility and radio propagation (presented in chapters 6 and 7), specially designed to correctly simulate traffic safety applications for VANETs. Finally, we presented the methodology followed to obtain the different simulation results, and the metrics we measured.

Chapter 5

Determining the Key Factors in VANETs

As we previously mentioned, simulation is a useful method to assess new proposals. This is mainly due to the high cost of deploying real testbeds in real scenarios. However, when simulating VANETs, the number of different factors affecting a proposed solution is usually very large, thus requiring a large amount of time and a high number of different simulations to evaluate the performance, advantages, and benefits of the proposals studied.

The 2k factorial methodology [Jai91] allows us to determine the most representative factors that govern the warning message dissemination performance in 802.11p based VANETs. The aim of this methodology is to reduce the simulation time required to analyze the performance of a given VANET system.

In a factorial design strategy, all factors are varied together (as opposed to one-at-time). So, a key advantage of the factorial design is that it allows researchers to find out the possible interactions among different factors. This methodology will allow us to also determine interdependencies among different factors.

5.1 Introduction

In this chapter, we present a statistical analysis based on the 2k factorial methodology to determine the representative factors affecting traffic safety applications in *Vehicular ad hoc networks* (VANETs). Our purpose is to determine what are the key factors affecting *Warning Message Dissemination* (WMD) in order to concentrate on such parameters, thus reducing the amount of required simulation time when evaluating VANETs.

This chapter is organized as follows: Section 5.2 presents some of the most relevant works using 2k factorial analysis in some research fields. Section 5.3 gives an overview of the 2k factorial approach. Section 5.4 introduces the different factors we have studied. In Section 5.5, we present the 2k factorial analysis made in our VANET scenario. The results obtained reflect which are the key factors to take into account when simulating VANETs. Finally, Section 5.6 concludes this chapter.

5.2 Related work

In the networking literature we can find several works that adopted the 2k factorial approach to discriminate among the many available parameters so as to determine the most relevant ones.

Gupta et al. [GACW07] studied *Distributed Network Control Systems* (D-NCS), a network structure and components that are capable of integrating sensors, actuators, communication, and control algorithms to suit real-time applications. They addressed the issue of D-NCS information security, as well its time-sensitive performance with respect to network security schemes. Standard statistical approaches, such as 2k factorial experiment design, analysis of variance, and hypothesis testing were used to study and estimate the effect of each factor on the system performance, with an emphasis on its security features.

Liu et al. [LMH08] studied the use of multipath routes to improve throughput, end-to-end delay and the reliability of data transport in *Wireless Sensor Networks* (WSNs). They reported the results of a series of simulations based on a factorial experimental design. Results showed that both the congestion window size, and the retry limit are key factors. Vaz de Melo et al. [VdMdCA$^+$08] studied how different WSNs can cooperate and save their energy. Simulation results revealed that different densities and data collecting rates among WSNs, the routing algorithm and the path loss exponent had major impact in the establishment of cooperation. The initial assessment of the impact of these factors was made through 2k factorial experimental analysis.

Perkins et al. [PHO02] studied and quantified the effects of various factors and their two-way interactions on the overall performance of MANETs. Using 2k factorial experimental design, they isolated and quantified the effects of five factors: (i) node speed, (ii) pause-time, (iii) network size, (iv) number of traffic sources, and (v) type of routing. They evaluated the impact of these factors on the throughput, routing overhead, and power consumption. In [PH02], authors investigated the impact of some characteristics on the performance of TCP in MANETs. Moreover, a factorial design experiment was conducted to quantify the effects and interactions that node speed and node pause time have over the throughput of TCP. Buchegger and Le Boudec [BLB02] proposed a protocol, called CONFIDANT, based on selective detection and isolation of misbehaving nodes. They presented a performance analysis of DSR fortified by CONFIDANT and compare it to regular defenseless DSR. A 2k factorial design was performed to find out which factors affect performance. McClary et al. [MSL08] designed a transport protocol that uses *Artificial Neural Networks* (ANNs) to adapt the audio transmission rate to changing conditions in a MANET. The response variables of throughput, end-to-end delay, and jitter were examined.

Cano et al. [CMS04] made an analysis of the behavior of mobile ad hoc networks when group mobility is involved. Using 2k factorial analysis they determined the most representative factors for protocol performance. It is shown that the number

Table 5.1: Example of results obtained in terms of warning notification time varying 2 factors

Number of vehicles	**Speed 10 km/h**	**Speed 80 km/h**
10	1 *second*	0.8 *seconds*
100	0.5 *seconds*	0.4 *seconds*

of groups parameter is more important than the number of nodes, and that the impact of the area size is almost negligible. Finally, it is evidenced that the presence of groups forces the network topology to be more sparse and therefore the probability of network partitions and node disconnections grows. In [AP07], the authors defined a performance index that can be used as an objective measure in the evaluation and comparison of ad hoc networking protocols. Using a statistical-based experimental design and analysis strategy, they illustrated the advantages of the proposed performance index by comparing two ad hoc networking systems over a wide range of networking scenarios.

As shown, the use of standard statistical approaches such as the 2k factorial analysis, is found in many other fields but seldom used in data communications. Moreover, to the best of our knowledge, this sort of statistical analysis has not been used in VANET research, and none of the research work currently available has formally identified the factors that significantly impact performance of warning message dissemination systems for VANETs.

5.3 The 2k Factorial Analysis

The number of possible factors and their values, or levels, can be very large when simulating vehicular ad hoc networks. In this section, we will explain how the 2k factorial analysis [Jai91] can be used to determine the most relevant factors that govern a system's performance.

The use of 2k factorial is important since it allows: (i) to reduce the overall number of simulations needed, (ii) to evaluate the relationship between different factors, and (iii) to reduce the required amount of simulation time needed.

The basic approach of this method is based on selecting a set of k parameters and determining 2 extreme levels (tagged with -1 and 1). An experiment is run for all the 2^k possible combinations of the parameters. From each experiment, we can also extract the $\binom{k}{2}$ two-factor interactions, the $\binom{k}{3}$ three-factor interactions, and so on.

For example, suppose that we have a Warning Message Dissemination system, and we want to study the impact of the number of vehicles (factor A) and the speed of these vehicles (factor B) in the warning notification time, i.e., the time required by normal vehicles to receive a warning message sent by a warning mode vehicle. Table 5.1 shows the results obtained after the simulations.

If we make a 2^2 factorial analysis, we can find out the impact of each factor (i.e., number of vehicles and speed), and their combination, in the studied metric

Table 5.2: Experiments defined by a 2^2 design

Experiment	**A**	**B**	**y**
1	-1	-1	y_1
2	1	-1	y_2
3	-1	1	y_3
4	1	1	y_4

(i.e., warning notification time). Table 5.2 shows the different experiments defined by the 2^2 design.

Let us define two variables x_A and x_B as presented in Equations 5.1 and 5.2:

$$x_A = \begin{Bmatrix} -1 & \text{if} & 10\, vehicles \\ 1 & \text{if} & 100\, vehicles \end{Bmatrix} \tag{5.1}$$

$$x_B = \begin{Bmatrix} -1 & \text{if} & speed = 10\, km/h \\ 1 & \text{if} & speed = 80\, km/h \end{Bmatrix} \tag{5.2}$$

The warning notification time (y) can be regressed on x_A and x_B using a non linear regression model:

$$\mathbf{y} = q_0 + q_A x_A + q_B x_B + q_{AB} x_A x_B \tag{5.3}$$

Substituting the four observations in the model, we get the following four equations:

$$1 = q_0 - q_A - q_B + q_{AB} \tag{5.4}$$

$$0.5 = q_0 + q_A - q_B - q_{AB} \tag{5.5}$$

$$0.8 = q_0 - q_A + q_B + q_{AB} \tag{5.6}$$

$$0.4 = q_0 + q_A + q_B + q_{AB} \tag{5.7}$$

These equations can be solved uniquely, and the regression equation is:

$$\mathbf{y} = 0.675 - 0.225 x_A - 0.075 x_B + 0.025 x_A x_B \tag{5.8}$$

The result is interpreted as follows: the mean warning notification time is 0.675 seconds, the effect of the number of vehicles is -0.075 seconds, the effect of the speed of the vehicles is -0.225 seconds, and the interaction between speed and number of vehicles accounts for 0.025 seconds.

Table 5.3: Sign table method of calculating effects in a 2^2 design

I	**A**	**B**	**AB**	**y**
1	-1	-1	1	1 *second*
1	1	-1	-1	0.5 *seconds*
1	-1	1	-1	0.8 *seconds*
1	1	1	1	0.4 *seconds*
2.7	-0.9	-0.3	0.1	Total
0.675	-0.225	-0.075	0.025	Total/4

5.3.1 Calculating the Effects of the Factors

In a 2k factorial analysis, by using the sign table method, we can get the results and detect variations which depend on the combination of factors. For a 2^2 design, the effects can be computed easily by preparing a 4 x 4 sign matrix as shown in Table 5.3.

The importance of a factor depends on the proportion of the metric *total variation* explained by the factor. The total variation of y is also known as *Sum of Squares Total* (SST) which can be calculated as follows:

$$Total\, variation\, of\; y = SST = \sum_{i=1}^{2^2}(y_1 - \overline{y})^2 \tag{5.9}$$

where $\overline{y}$ denotes the mean of responses from all four experiments. For a 2^2 design, the variation can be divided into three parts:

$$SST \quad = \quad 2^2q_A^2 + 2^2q_B^2 + 2^2q_{AB}^2 \tag{5.10}$$

These parts can be expressed as a fraction; for example:

$$Fraction\, of\; variation\, explained\, by\; A = \frac{SSA}{SST} = \frac{2^2q_A^2}{SST} \tag{5.11}$$

Hence, we can indicate the percentage of variation of each studied metric explained by each factor. The more percentage of variation, the more impact this factor has in the measured metric. In our example, we obtained that the number of vehicles accounts for 89.01% of the total variation of the warning notification time, the speed of the vehicles accounts for 9.89%, and their combination accounts for the remaining 1.10%. Therefore, the number of vehicles is the most important factor which affects the warning notification time.

The outcome of the 2k factorial analysis allows us in sorting out factors in the order of impact. At the beginning of a performance study, the number of factors and their levels is usually large. A full factorial design with such a large number of factors and levels may not be the best use of available resources. The first step should be to reduce the number of factors and to choose those factors that have significant impact on the performance.

5.4 Factors to Study in VANETs

Some previous works have studied the most important factors in MANETs. Nevertheless, VANETs have special characteristics that make them different from MANETs. Hence, more research is required in order to identify the key factors that have a strong impact on its performance. In this section we identify and describe the most important factors in VANET *Warning Message Dissemination* (WMD). We will then focus on those factors along the rest of this thesis.

We start our analysis by selecting the following eight factors which have been widely used in the literature: (i) the number of warning mode vehicles, (ii) the total number of vehicles, (iii) the channel bandwidth, (iv) the broadcast scheme, (v) the radio propagation model, (vi) the periodicity of messages, as well as (vii) the maximum speed in the outskirts, and (viii) the transmission range.

5.4.1 Number of Warning Vehicles

In traffic safety applications, vehicles may send safety messages to other vehicles in order to prevent collisions or to ask for emergency services. We consider that vehicles may operate in warning or in normal mode. Warning mode vehicles inform other vehicles about their abnormal status by sending warning messages periodically. Normal mode vehicles participate in the diffusion of these warning packets, and periodically, they also send *beacons* with information about themselves, such as their positions and speed.

This factor is important since the more vehicles in the warning mode are there in a scenario, the more network traffic there will be, thus increasing redundant rebroadcasts which provoke heavy contention and long-lasting collisions. Figure 5.1 shows an example of a WMD scheme in a VANET, where a warning mode vehicle disseminates information about a traffic incident.

5.4.2 Number of Vehicles

In VANETs, the number of nodes can be particularly high, which usually provokes that VANET simulations require quite a long time to finish. Moreover, many network simulators do not scale well, and so simulating VANETs with more that 500 vehicles consumes a significant amount of time and resources.

As shown in previous works, this factor seems to be important to measure WMD performance in VANET scenarios.

5.4.3 Channel Bandwidth

In radio communications, bandwidth is the width of the frequency band used to transmit the data. Channel spacing is a term used in radio frequency planning that describes the frequency difference between adjacent allocations in a frequency plan.

The 802.11p standard allows two different bandwidth configurations: (i) 3 Mbit/s with a 10 MHz channel spacing, and (ii) 6 Mbit/s with a 20 MHz channel spacing.

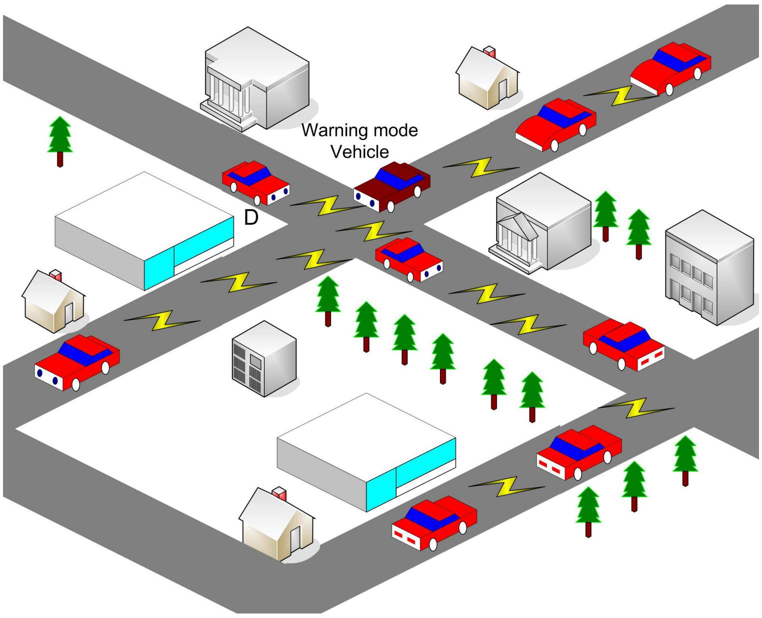

Figure 5.1: Warning Message Dissemination (WMD) in a VANET.

Since vehicular information delivery systems support applications such as cooperative driving among cars on the road, traffic safety, or infotainment applications, we think that channel bandwidth requirements could change based on the selected application. For the specific case of WMD mechanisms, the overall capacity of the channel can affect the effectiveness of warning dissemination schemes if the number of potential transmitters is high.

5.4.4 Broadcast Scheme

Another important factor in Warning Message Dissemination in VANETs is the selected broadcast scheme. In VANETs, intermediate vehicles act as relays to support end-to-end vehicular communications. For applications such as route planning, traffic congestion control, and traffic safety, the flooding of broadcast messages commonly occurs. However, flooding results in many redundant rebroadcasts, heavy channel contention, and long-lasting message collisions (usually known as the broadcast storm problem) [TNCS02].

In the past, several approaches have been proposed to solve the broadcast storm problem in ad hoc networks. They include: (i) the counter-based scheme, which uses a counter to keep track of the number of times the broadcast message is received in order to inhibit the rebroadcast in case a message is received a certain number of times, (ii) the distance-based scheme, in which the relative distance between vehicles is used to decide whether to rebroadcast or not, (iii) the location-based scheme, which is very similar to the distance-based scheme, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation of the additional coverage of a rebroadcast, and (iv) the cluster-based scheme, where vehicles are grouped in clusters, and only one member of each cluster (the cluster head) can rebroadcast the warning messages. In our experiments we use both the counter-based scheme and the location-based scheme to assess the relevance of the broadcast scheme adopted.

5.4.5 Radio Propagation Model

We observe that the most widely used simulators, such as ns-2, Glomosim, QualNet and OPNET have not accurately simulated the *Radio Propagation Model* (RPM) in vehicular environments. In particular, they do not take into account the physical obstacles present in urban environments (mostly buildings). For example, the commonly used *Two-Ray Ground* (TRG) radio propagation model ignores effects such as *Radio Frequency* (RF) attenuation due to buildings and other obstacles. Nevertheless, for 802.11p-based VANETs, the received signal will largely depend on the presence of obstacles.

In the literature, most works related to VANETs employ very simplistic RPMs, ignoring the effects that buildings have on radio signals propagation. In this Thesis, we include as an alternative the *Building and Distance Attenuation Model* (BDAM) [MTC+09b], and the *Real Attenuation and Visibility Model* (RAV) [MFC+10a], two realistic RPMs specifically designed for IEEE 802.11p based VANETs that increase the level of realism of phenomena occurring at the physical layer, thereby allowing researchers to obtain more accurate and meaningful results. BDAM and RAV consider that communication will only be possible when the received signal is strong enough and vehicles are within line-of-sight. It also takes into consideration that, at a frequency of 5.9 GHz (i.e., the frequency band of the 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 the vehicles are in line-of-sight. Sections 7.2.3 and 7.2.4 present BDAM and RAV in detail.

5.4.6 Message Periodicity

As mentioned previously, warning mode vehicles inform other vehicles about their status by sending warning messages periodically. Normal mode vehicles participate in the diffusion of these warning packets, while they also send periodic *beacons* with information such as their positions, speed, etc.

Similarly to the number of warning vehicles, the more warning messages are sent at the same time, the more redundant rebroadcasts, channel contention, and message collisions there will be. Thus, message periodicity seems to be an important factor that offers a trade-off between performance and overhead.

5.4.7 Speed of Vehicles

In VANETs, nodes move within a constrained but highly variable topology due to the high mobility. In fact, vehicles move at higher speeds, especially in highways.

In MANETs, node speed ranges from 0 to 5 m/s, while in VANETs speed ranges from 0 to 40 m/s.

5.4.8 Transmission Range

The transmission range is a very important factor in wireless networks, and also in VANET simulations, since the wider the transmission range, the easier the warning message dissemination will be.

When simulating wireless networks, most network simulators assume that the warning packets sent by warning mode vehicles can be received by all vehicles within the radio range. For example, ns-2 assumes that signals have a perfect 250m radius range, which is overly optimistic for urban environments. Nevertheless, for 802.11p-based VANETs, the received signal strength will largely depend on the distance from the sender. Consequently, simulation results so obtained are unlikely to accurately reflect system performance in the real world.

In our simulations, we compare two different RPMs: (i) the Two Ray Ground model, that considers a perfect radius range, and (ii) the BDAM model, that considers the signal attenuation due to the distance between vehicles by adding a probability function to estimate whether messages are correctly received or not within the radio range.

5.5 Factors Determination Using 2k Factorial Analysis

In this section, we use the 2k factorial analysis [Jai91] to determine the most relevant factors that govern Warning Message Dissemination performance, and to reduce the required amount of simulation time.

We consider 8 factors, previously presented in Section 5.4, which we felt are necessary. They are listed in Table 5.4. We tag each of the factors with A, B, C, ...H accordingly, as stated in the table. Thereafter, we specify two possible environments which are described by two different levels, i.e. Level -1 and Level 1. Each level provides different parameter values to define the environment.

In Table 5.5 we indicate the percentage of variation of each studied metric explained by each factor. The more the percentage of variation, the more impact this factor has in the measured metric.

Results of our 2k factorial analysis show that:

- The average number of blind vehicles is largely affected by the number of vehicles (B), the transmission range (H), and their combination (BH).
- The average number of packets received per vehicle is largely affected by the radio propagation (E), the transmission range (H), and their combination (EH).
- The average time required to complete the propagation process is largely affected by the radio propagation (E), the transmission range (H), and their combination (EH).

Table 5.4: Factors considered and their values

Factor	**Level -1**	**Level 1**
warning vehicles (A)	3	10
number of vehicles (B)	100	300
channel bandwidth (C)	$3Mbps$	$6Mbps$
broadcast scheme (D)	counter-based	location-based
radio propagation (E)	TRG	BDAM
periodicity of messages (F)	1 $packet/s$	20 $packets/s$
maximum speed (G)	4 $meters/s$	28 $meters/s$
transmission range (H)	$100m$	$500m$

Based on the above outcome, we can state that having both a higher transmission range (i.e., H), and a higher density of nodes (i.e., B) is very important for reducing the number of blind nodes. Also, to reduce the time required for the complete propagation of warning messages and the number of packets received per node, the key factors to be accounted for are the transmission range and the selected radio propagation model (i.e., factors H and E). According to the obtained results, in the next subsections we further evaluate the impact of the transmission range, the radio propagation model, and the number of vehicles in warning message dissemination.

5.5.1 Evaluating the Impact of the Transmission Range

Figure 5.2 and Table 5.6 show the simulation results when varying the transmission range of vehicles while maintaining the rest of the parameters unaltered. As expected, the warning notification time is lower when the transmission range increases. Information reaches about 60% of the vehicles in less than 0.8 seconds when the transmission range is 200 meters, and in only 0.17 seconds when the range is equal to 500 meters.

The behavior in terms of percentage of blind vehicles also depends highly on this factor. In fact, when the transmission range is higher, information reaches more vehicles (up to 92% for 500 meters, so that there are only 8% of blind vehicles). Nevertheless, when the transmission range is reduced to 100 meters, there are 98% of blind vehicles, which prevents the WMD from operating correctly. This occurs because the flooding propagation of the messages works better with higher transmission ranges. Finally, as shown in Table 5.6, the number of packets received per vehicle also increases substantially when the transmission range increases.

5.5.2 Evaluating the Impact of the Radio Propagation Model

Figure 5.3 shows the warning notification time when varying the radio propagation model from the traditional *Two-Ray Ground* (TRG) model to the more realistic BDAM model, proposed in Section 7.2.3.

As shown, the warning notification time is lower when using the TRG model. Information reaches about 60% of the vehicles in less than 0.12 seconds, and prop-

Table 5.5: The percentage of variation explained using the sign table method up to the combination of 2 factors

Factors	**Variation explained (%)**		
	% of blind vehicles	*number of packets received*	*seconds to end propagation*
A	0.00	6.97	1.64
B	**15.73**	1.26	0.42
C	0.00	1.48	0.14
D	0.00	4.62	0.02
E	0.16	**15.45**	**28.10**
F	0.00	0.00	0.00
G	0.10	0.10	0.02
H	**63.68**	**30.41**	**30.05**
AB	0.00	0.35	0.74
AC	0.00	0.38	0.23
AD	0.00	0.38	0.00
AE	0.00	3.07	0.22
AF	0.00	0.00	0.00
AG	0.00	0.01	0.07
AH	0.00	6.86	0.62
BC	0.00	0.17	0.01
BD	0.00	0.23	0.00
BE	0.05	0.02	0.90
BF	0.00	0.00	0.00
BG	0.05	0.19	0.31
BH	**19.96**	1.09	4.63
CD	0.00	0.68	0.22
CE	0.00	1.36	0.01
CF	0.00	0.00	0.00
CG	0.00	0.00	0.00
CH	0.00	1.48	0.14
DE	0.00	3.41	0.08
DF	0.00	0.00	0.00
DG	0.00	0.06	0.01
DH	0.00	4.50	0.08
EF	0.00	0.00	0.00
EG	0.06	0.03	0.09
EH	0.15	**15.37**	**31.14**
FG	0.00	0.00	0.00
FH	0.00	0.00	0.00
GH	0.06	0.08	0.12

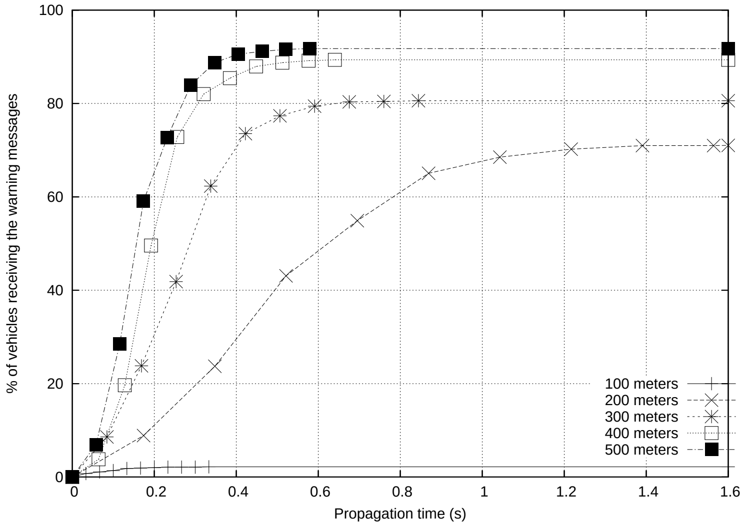

Figure 5.2: Cumulative histogram for the time evolution of disseminated warning messages when varying the transmission range.

Table 5.6: Blind vehicles and packets received per vehicle when varying the transmission range

Tx range (in meters)	**% of blind vehicles**	**packets received**
100	98%	254.20
200	28%	835.00
300	19%	1401.40
400	10%	1603.07
500	8%	2030.00

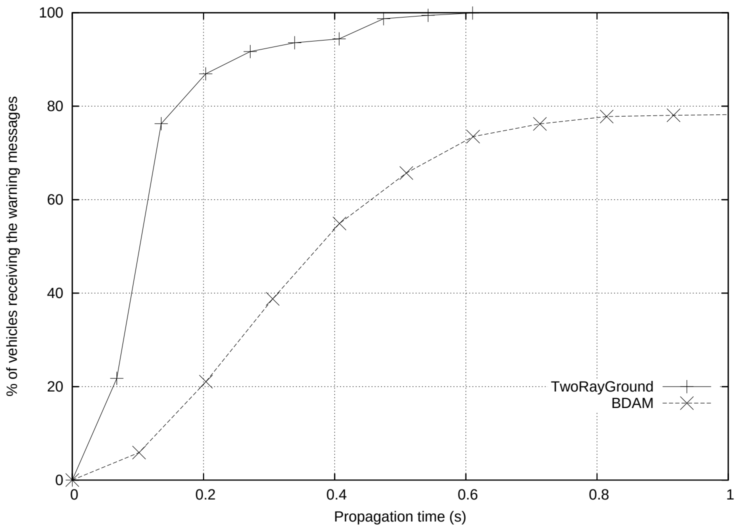

Figure 5.3: Cumulative histogram for the time evolution of disseminated warning messages when varying the RPM used.

agation is completed in only 0.62 seconds. When using the BDAM model, the system needs 0.45 seconds to reach 60% of the vehicles, and propagation was completed in 1 second.

The behavior in terms of percentage of blind vehicles and the number of packets received also highly depends on this factor. In fact, when using the TRG model, there are no blind vehicles, while we find 22% of blind vehicles when using BDAM. So, when the model is more realistic, more time is needed to reach the same percentage of vehicles, and thus the percentage of blind vehicles increases. This occurs because the TRG model is really optimistic, and it does not account for the presence of obstacles in signal propagation. Moreover, the average number of packets received per vehicle highly differs depending on the model (see Table 5.7). The number of packets received decreases considerably for BDAM since signal propagation encounters more restrictions [MTC+09b].

The results show that using more realistic models tends to reduce protocol performance, allowing us to better understand the impact of buildings and obstacles along the road on car-to-car communications. Although the BDAM model yields poorer performance results than TRG, it is in fact a more realistic radio propagation model, which should be considered in future VANET simulations.

5.5.3 Evaluating the Impact of the Number of Vehicles

Figure 5.4 shows the simulation results when varying the number of vehicles while maintaining the rest of the parameters unaltered. We selected 50, 100, 200, 300, and 400 vehicles. As expected, the warning notification time is lower when the vehicle density increases. When simulating with 300 and 400 vehicles, information

Table 5.7: Blind vehicles and packets received per vehicle when varying the Radio Propagation Model

RPM	**% of blind vehicles**	**packets received**
TRG	0%	4783.93
BDAM	22%	1179.00

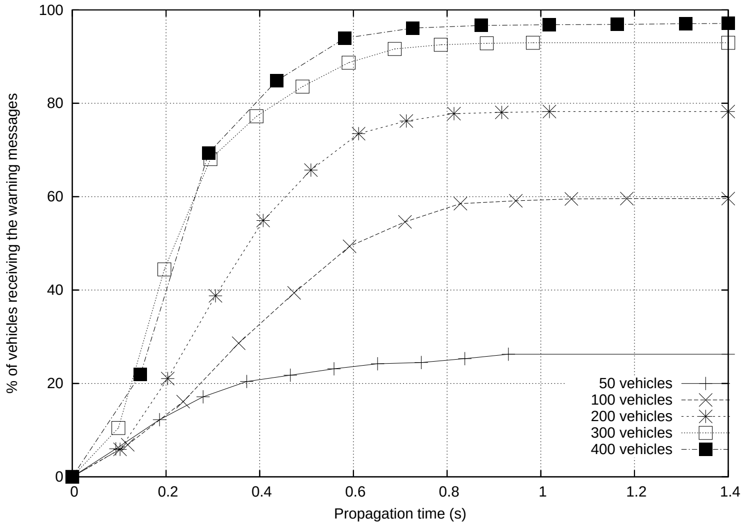

Figure 5.4: Cumulative histogram for the time evolution of disseminated warning messages when varying the number of vehicles.

reaches about 60% of the vehicles in only 0.26 seconds, and the propagation process is completed in 1.4 seconds.

Table 5.8 shows the percentage of blind vehicles and the number of packets received per vehicle when varying the number of vehicles. The behavior in terms of percentage of blind vehicles highly depends on this factor. In fact, when vehicle density is high, the percentage of blind vehicles is almost negligible. This characteristic is explained because the flooding propagation of warning messages works better with higher vehicle densities. As for the number of packets received per vehicle, this number increases when increasing vehicle density. Note that, due to collisions, the number of packets received per vehicle slightly differs when simulating 300 or 400 vehicles.

5.5.4 Lessons Learnt and Guidelines for Future Research

The 2k factorial analysis reflected that the key factors to take into account when simulating VANETs are: (i) the transmission range, (ii) the radio propagation model used, and (iii) the number of vehicles. By evaluating the impact of each factor one by one, we confirmed the outcome of the 2k factorial analysis. We observed

Table 5.8: Blind vehicles and packets received per vehicle when varying the number of vehicles

Vehicles	**% of blind vehicles**	**packets received**
50	73%	364.00
100	40%	481.73
200	22%	1085.47
300	6%	2116.33
400	2%	2215.67

that the propagation of warning messages works better with higher transmission ranges and higher vehicle densities. Moreover, although the use of more realistic RPMs tends to reduce protocol performance, realistic RPMs such as the BDAM model are required in future VANET simulations. In Section 7.2 we propose some realistic RPMs and evaluate their performance.

Results also showed that other important factors, such as the broadcast scheme used, the channel bandwidth, the speed of vehicles, and the periodicity of messages, have little impact in the warning message delivery process.

The obtained results suggest us to account for a compound key factor: neighbor density. This factor combines two of the key factors (see Equation 5.12) into a single one, thus reducing the number of factors that must be taken into account by researchers for future VANET studies:

$$neighbor\ density = \frac{number\ of\ vehicles \cdot Tx\ range}{map\ area} \tag{5.12}$$

Some authors have previously used this term in Intelligent Transportation Systems [TFP00], although they really referred to the average number of the potential neighbors, i.e., the density of vehicles (see Equation 5.13).

$$neighbor\ density \neq vehicle\ density = \frac{number\ of\ vehicles}{map\ area} \tag{5.13}$$

To calculate the neighbor density, we account for the transmission range (as other authors in [NS09, FT04, SRLS07]) since we consider that one vehicle is a neighbor of another only if this vehicle can be reached in one hop, i.e. it is within its transmission range.

Figure 5.5 and Table 5.9 show the simulation results when varying the neighbor density while maintaining the rest of parameters unaltered. As shown, all the metrics highly depend on neighbor density. With a small number of neighbors, the warning notification time is higher, the percentage of blind vehicles is very high, and the number of packets received is very low. Nevertheless, with a large number of neighbors, the system needs less time to complete the propagation process, the percentage of blind vehicles is null, and the number of packets received increases. Results show that, when there are 50 or more neighbors per vehicle, the percentage of blind vehicles is almost negligible and the warning information reaches all

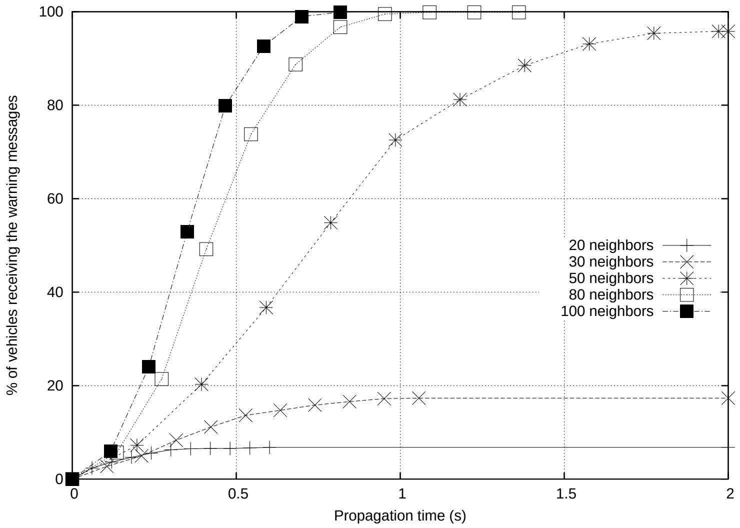

Figure 5.5: Cumulative histogram for the time evolution of disseminated warning messages when varying the neighbor density.

Table 5.9: Blind vehicles and packets received per vehicle when varying the neighbor density

Neighbors	**% of blind vehicles**	**packets received**
20	93%	272.20
30	83%	295.20
50	4%	625.40
80	0%	1355.53
100	0%	1428.20

vehicles in a reasonable time, meaning that the Warning Message Dissemination scheme achieves the desired degree of effectiveness.

5.6 Summary

In this chapter, we identified and described the different factors to be taken into account when simulating VANETs. Since the number of possible factors can be very large, we identified the representative factors by using the 2k factorial analysis. The purpose is to reduce the required simulation time in future research.

Simulation results show that the key factors affecting the delivery of warning messages are: (i) the transmission range, (ii) the radio propagation model used, and (iii) the number of vehicles. Some factors such as message periodicity, channel bandwidth, the broadcast scheme used, and the speed of vehicles did not have a significant impact on the metrics considered in our study. Based on this analysis, we evaluated a compound key factor: neighbor density. This factor combines the number of vehicles with the transmission range, and the map area into a single entity, reducing the number of factors that must be taken into account for VANET researchers to evaluate the benefits of their proposals.

Results obtained from our simulations confirmed that neighbor density is a crucial factor. In fact, performance parameters such as the propagation delay, the percentage of blind vehicles, and the number of packets received per vehicle highly depend on it. We believe that the results of our analysis can save time by discarding unnecessary factors when performing simulations for VANET-related research.

Chapter 6

Improved Mobility Models for Vehicular Networks

One of the important issues when creating a simulation environment in VANETs is to correctly model realistic scenarios, providing accurate and realistic vehicular mobility description at both macroscopic and microscopic levels. Another challenge is to be able to dynamically alter this vehicular mobility as a consequence of the vehicular communication protocols. In this chapter, we focus on the mobility models for Vehicular Networks. Specifically, we present the approaches we have proposed to realistically model vehicular mobility patterns in VANETs.

6.1 Introduction

Existing mobility models try to closely represent the movement patterns of users. These models provide a suitable environment for the simulation, study, and evaluation of ad hoc communication performance, various media access, routing, and emergency warning protocols.

This chapter is organized as follows: Section 6.2 presents our proposed VANET mobility environments. In that section, we introduce three different approaches: (i) our CityMob v.1 mobility generator, specially designed to model vehicles traveling in a Manhattan-based urban scenario, (ii) our CityMob v.2 mobility generator, highlighting the improvements with respect to version 1, to model vehicles' movements in a more realistic way, and (iii) our mobility environment based on the SUMO traffic generator, in order to model real roadmaps in VANETs. Sections 6.3 and 6.4 present a qualitative and a performance comparison of the most relevant mobility generators, respectively. Finally, Section 6.5 concludes this chapter.

6.2 Proposed Mobility Environment

The general problem of modeling the behavior of vehicles belonging to a vehicular network does not have a unique or straightforward solution. Mobility patterns are dependent on various factors, such as the physical environment, the user's objectives, and the user's inter-dependencies. Previous works [HKG+01, CBD02] showed that these models can greatly affect simulation results, and so realistic movement patterns are compulsory when simulating VANETs.

In this section we propose three different mobility generation environments: (i) CityMob v.1, (ii) CityMob v.2, and (iii) a SUMO-based mobility generation environment. Next, we present these proposals.

6.2.1 CityMob v.1 Mobility Generator

We developed a tool that allowed us to create realistic VANET simulations that is completely compatible with the ns-2 simulation tool. This tool was developed in C, and its name is *CityMob*.

CityMob[1] is a mobility pattern generator specially designed to investigate different mobility models in VANETs, and their impact on inter-vehicle communication performance. CityMob creates urban mobility scenarios and simulates damaged cars using the network to send information to other vehicles, trying to prevent accidents or traffic jams.

We propose three different mobility models that combine a certain level of randomness, while trying to represent some realistic environments. The models are:

1. The *Simple Model* (SM), which models vertical and horizontal mobility patterns without direction changes. Traffic lights are not supported either.

2. The *Manhattan Model* (MM), which models the city 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 vehicle in every moment will be random, and it can not be repeated in two consecutive movements. Moreover, this model simulates traffic lights at random positions (not only at crossings), and with different delays. When a vehicle encounters a traffic light, it will remain stopped until the traffic light turns to green.

3. The *Downtown Model* (DM), which 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 the downtown, and vehicles must move more slowly than in the outskirts. In our experiments, vehicles crossing the downtown have a random speed between 25 and 60 km/h, while the speed in the outskirts, usually higher, can be selected by the user.

   The Downtown area is defined by the coordinates ($start\_x$, end_x, $start\_y$, end_y) and can never cover more than 90% of the total map area.

   Parameter p is used to establish the probability of a vehicle being initially located inside the downtown area, and also the probability that vehicles on the outskirts move into the downtown. Remember that, once a vehicle enters

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[1] `CityMob's` source code is available at http://www.grc.upv.es/

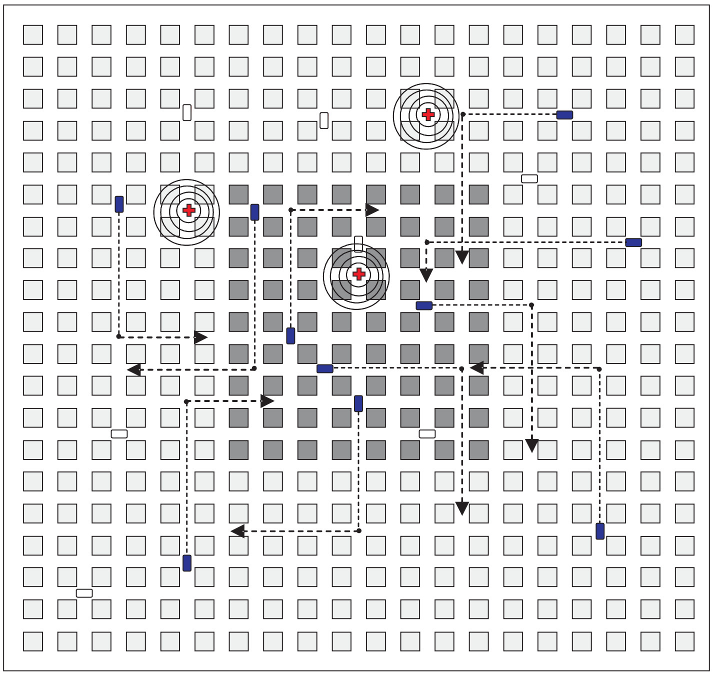

Figure 6.1: Example of a downtown scenario.

this area, it will move slower. The remaining features are the same as for the Manhattan mobility model.

Figure 6.1 shows an example of this model. Notice that the darker buildings area represents the downtown. Dark rectangles represent vehicles, shadowed rectangles represent vehicles stopped at traffic lights, and crosses represent damaged cars sending warning packets.

We do not distinguish among different types of vehicles (cars, trucks or taxis), but only between normal vehicles and damaged ones. The user has to set the mobility model, the total number of vehicles, the simulation time, the map size, the maximum speed value, the distance between consecutive streets, and the number of damaged vehicles.

6.2.1.1 CityMob's v.1 features

The standard scenario commonly used for MANETs tends to be either not useful in VANETs or too limited in scope [HHCW05]. In CityMob, a City is a square area, and streets will be arranged in a Manhattan style grid, with a uniform block size across the simulation area (this size can be set by the user). All streets are two-way, with lanes in both directions. Car movements are constrained by these lanes. Vehicles will move with a random speed lower than the maximum one defined by the user, and the movement pattern will be constrained by the mobility model selected. Damaged vehicles will remain stopped during the entire simulation time.

Within our simulation framework, we generate mobility traces for the three mobility models proposed according to the following guidelines:

1. The city is simulated in the same way for the three models, with a Manhattan grid map. Map width and height are configurable parameters.
2. The distance between streets is also configurable, logically limited by map size. There must be a minimum number of crossings to allow vehicles to change their direction.
3. Users can change the number of simulated vehicles and the number of damaged nodes (statically located throughout the simulation area). Every node will start at a random position inside the map, although in the Downtown model the probability of starting inside the downtown is greater.
4. Speed can vary according to the map area, changing throughout the simulation. Every node will travel with a random speed for each movement, always lower than the maximum speed defined by the user.
5. There will be no accidents or crashes between nodes (in the same or different direction). We assumed that the number of lanes are enough for the vehicles that are traveling in the city.

We have to mention the presence of traffic lights (for the Manhattan and Downtown models). Vehicles will simulate traffic lights by stopping themselves randomly. This way, simulation is more realistic since in a city traffic lights are not systematically distributed on streets, and it also help us to model other unforeseen traffic events, e.g., when a vehicle suddenly stops. This characteristic is one of the basic differences compared to another related work [HHCW05].

6.2.1.2 Installation and operation

CityMob v.1 has been implemented using the C programming language and it is distributed under a GNU/GPL license.

The use of CityMob is very simple. We only have to execute the application followed by the required parameters in order to generate the desired mobility trace file.

An example of CityMob could be:

```
./citymob -m 3 -n 25 -t 1200 -s 40 -w 1000 -h 1000 -d 50 -a 3
-x 300 -y 300 -X 700 -Y 700 -p 0.80
```

The different parameters that a user can define are the following: $-m$ that allows to select one of the three mobility models, i.e., 1 stands for Simple, 2 stands for Manhattan, and 3 for Downtown; $-n$ that configures the number of nodes in the simulation. This parameter ranges between 1 and 1000; $-t$ that allows to establish the total simulation time; $-s$ that configures the maximum speed that a node can achieve, measured in meters per second. This value ranges between 14 m/s (50km/h) to 60 m/s (220 km/h). For the Downtown model, this value is only applied in the outskirts; $-w$ and $-h$, that allow to set the size of the map in meters; $-d$ that allows to specify the distance between streets, in meters. If we take x as the minimum value between $-w$ y $-h$ parameters, the value of $-d$ can not be bigger than x divided by 4; $-a$ determines the number of nodes damaged during the simulation.

In CityMob v.1, an accident is modeled by a node that remains static throughout the simulation. The position of these nodes will be random.

Finally, there are also some parameters that are only related to the Downtown model. These parameters are $-x$, $-y$, $-X$, $-Y$ and $-p$. The first four are used to define the downtown of the city (they represent the coordinates x and y). The downtown can never cover more than 90% of the total map area. Parameter $-p$ is used to establish the probability for nodes to start the simulation inside the downtown, and also the probability for nodes in the outskirts to move towards the downtown.

Once we have generated the mobility scenarios, we can start the simulation. The configuration is done through TCL scripts. On the one hand we have a main file that contains basic options that will be used by ns-2 for the simulation; on the other hand we have the traffic file that defines how wireless transmitters and receivers work. In our study we used the Diff_Sink agent as a transmission agent.

Table 6.1: Some important options in the TCL script

set opt(adhocR)	FLOODING	# routing protocol
set opt(duplicate)	"enable-dup"	# protocol option
set opt(traf)	"city-traffic.tcl"	# traffic file
set opt(tr)	"flooding.tr"	# trace file
set opt(nam)	"flooding.nam"	# nam file
set opt(sc)	"city-scen"	# scene file
set opt(x)	1000	# x axis of the map
set opt(y)	1000	# y axis of the map
set opt(nn)	25	# number of nodes
set opt(stop)	60.0	# simulation time
set opt(prestop)	59	# instant to prepare

Each damaged vehicle periodically broadcasts information about itself. So, the routing protocol used is *flooding*. When a vehicle receives a broadcast message, it stores and immediately forwards it by re-broadcasting the message.

Notice that, in our scenarios, warning messages should be propagated to all neighbors up to a certain number of hops. Hence, the use of flooding fits our purpose adequately. In some environments, flooding can generate many redundant transmissions and saturate the network, which may cause the well-known broadcast storm problem where serious redundancy, contention and collisions produce information losses [NTCS99]. Nevertheless, for our requirements, this protocol is very useful because we desire that the warning packets sent by damaged nodes can be received by all vehicles of the map, and this protocol offers the best reliability in terms of coverage. In Chapter 8, we address the broadcast storm problem in VANETs.

Figure 6.2 shows an example of flooding transmission started from a damaged vehicle (the one with the cross on top).

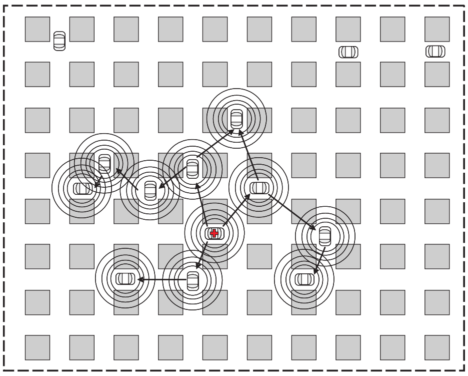

Figure 6.2: Example of flooding transmission from a damaged node.

6.2.2 CityMob v.2 Mobility Generator

CityMob v.2[2] has been implemented using the Java programming language and it is distributed under a GNU/GPL license. CityMob v.2 is a ns-2 compatible VANET mobility model generator which implements an enhanced version of the *Downtown Model* (DM).

In the DM model, streets are arranged in a Manhattan style grid with a uniform block size across the simulation area. All streets are two-way, with lanes in both directions. Car movements are constrained by these lanes. Vehicles will move with a random speed within an user-defined range of values. The DM model also simulates traffic lights at random positions (not only at crossings), and with different delays. DM adds traffic density in a way similar to a real town, where traffic is not uniformly distributed. Hence, there will be zones with a higher vehicle density. These zones are usually in the downtown, and vehicles must move more slowly than those in the outskirts.

With respect to version 1, CityMob v.2 has also the following capabilities: (a) multiple lanes in both directions for every street, (b) vehicle queues due to traffic jams, and (c) the possibility of having more than one downtown.

6.2.3 Proposed SUMO-based Mobility Environment

CityMob v.1 and v.2 were proposed to simulate more realistic VANET scenarios. Nevertheless, in order to simulate real roadmaps and to use a validated and widely used mobility generator, we proposed using both the openstreepmap tool available at www.openstreetmap.org to get real map scenarios. Additionally, we rely on SUMO to generate the vehicles and their movements within these scenarios. The functionality provided by this model is twofold: it constrains vehicle movement to the streets defined in the roadmap, and it limits their mobility according to the vehicular congestion and traffic rules.

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[2] `CityMob v.2` source code is available at http://www.grc.upv.es/

The Simulation of Urban MObility (SUMO) [KR07] is an open source, microscopic, space-continuous traffic simulator designed to handle large road networks. The car microscopic movement model in SUMO is a car following model and includes a stochastic traffic assignment modeled by a probabilistic route choice according to driver models.

The generation of the road network is the first step of a SUMO simulation. By using a digital roadmap as input (obtained from openstreetmap.org in our simulations), SUMO obtains the topology of roads and their speed limits. The speed limit is assigned according to the road types defined in its map database. The traffic lights are also modeled by SUMO automatically.

The second step is the generation of traffic. SUMO provides several means to generate random vehicle routes, although random routes generation could not be realistic enough. Taking the idea from route management and execution of the Street Random Waypoint Model (STRAW) [str08], a vehicle randomly selects a destination in the area, and then chooses a shortest path (which consists of a series of road segments) to go to. When it arrives at the destination, a new destination is chosen again. By joining these routes, we get a route long enough for our simulation duration.

It seems obvious that each driver is trying to use to shortest path through the network. However, when all vehicles adopt this strategy, some of the roads - mainly the arterial roads - would get congested, thus reducing the benefit of using them. Solutions for this problem are known to traffic research as user assignment. To solve this, several approaches are available and SUMO uses the dynamic user assignment (DUA) approach developed by Christian Gawron [Gaw98].

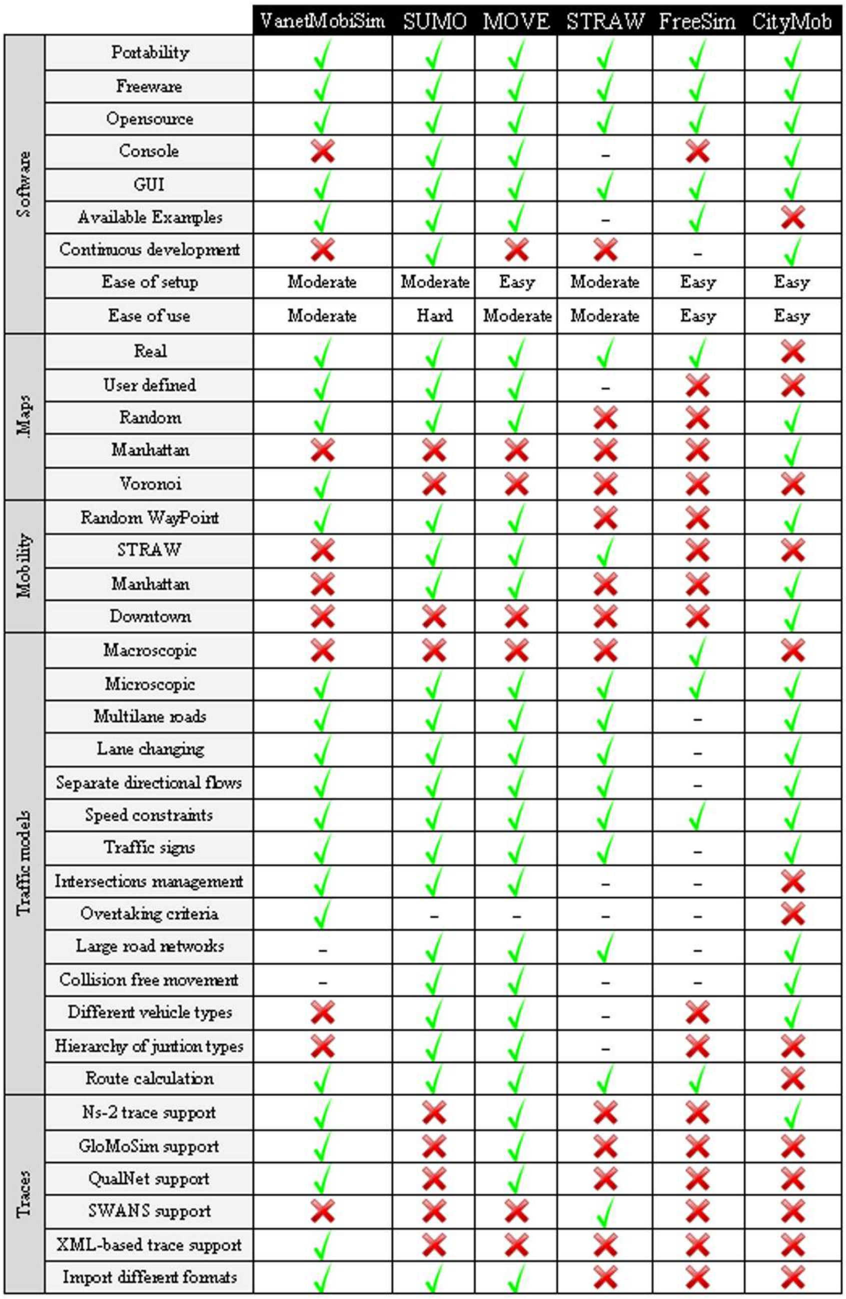
The steps followed to generate traces in our proposed mobility environment are the following:

1. Obtain a real city map data from openstreetmap.org (*.osm)
2. Obtain SUMO-compatible road network description converting the openstreetmap.org file (*.net.xml)
3. Generate vehicle routes randomly
4. Perform the traffic simulation and dump the mobility output trace
5. Convert the output trace to be compatible with ns-2 using the MOVE application.

6.3 Qualitative Comparison of Mobility Generators

Table 6.2 presents a summary of the studied vehicular mobility generators (previously presented in Section 4.3.1.2) focusing on their main characteristics. We have grouped the comparisons into five different categories: (a) Software characteristics, (b) Maps types, (c) Mobility models supported, (d) Traffic models implemented, and (e) Trace formats supported.

Table 6.2: A comparison of the studied mobility generators



		VanetMobiSim	SUMO	MOVE	STRAW	FreeSim	CityMob
Software	Portability	✓	✓	✓	✓	✓	✓
	Freeware	✓	✓	✓	✓	✓	✓
	Opensource	✓	✓	✓	✓	✓	✓
	Console	✗	✓	✓	–	✗	✓
	GUI	✓	✓	✓	✓	✓	✓
	Available Examples	✓	✓	✓	–	✓	✗
	Continuous development	✗	✓	✗	✗	–	✓
	Ease of setup	Moderate	Moderate	Easy	Moderate	Easy	Easy
	Ease of use	Moderate	Hard	Moderate	Moderate	Easy	Easy
Maps	Real	✓	✓	✓	✓	✓	✗
	User defined	✓	✓	✓	–	✗	✗
	Random	✓	✓	✓	✗	✗	✓
	Manhattan	✗	✗	✗	✗	✗	✓
	Voronoi	✓	✗	✗	✗	✗	✗
Mobility	Random WayPoint	✓	✓	✓	✗	✗	✓
	STRAW	✗	✓	✓	✓	✗	✗
	Manhattan	✗	✓	✓	✗	✗	✓
	Downtown	✗	✗	✗	✗	✗	✓
Traffic models	Macroscopic	✗	✗	✗	✗	✓	✗
	Microscopic	✓	✓	✓	✓	✓	✓
	Multilane roads	✓	✓	✓	✓	–	✓
	Lane changing	✓	✓	✓	✓	–	✓
	Separate directional flows	✓	✓	✓	✓	–	✓
	Speed constraints	✓	✓	✓	✓	✓	✓
	Traffic signs	✓	✓	✓	✓	–	✓
	Intersections management	✓	✓	✓	–	–	✗
	Overtaking criteria	✓	–	–	–	–	✗
	Large road networks	–	✓	✓	✓	–	✓
	Collision free movement	–	✓	✓	–	–	✓
	Different vehicle types	✗	✓	✓	–	✗	✓
	Hierarchy of juntion types	✗	✓	✓	–	✗	✗
	Route calculation	✓	✓	✓	✓	✓	✗
Traces	Ns-2 trace support	✓	✗	✓	✗	✗	✓
	GloMoSim support	✓	✗	✓	✗	✗	✗
	QualNet support	✓	✗	✓	✗	✗	✗
	SWANS support	✗	✗	✗	✓	✗	✗
	XML-based trace support	✓	✗	✗	✗	✗	✗
	Import different formats	✓	✓	✓	✗	✗	✗

Table 6.3: Parameters used for performance simulation of different VANET mobility generators

Parameters	**Values**			
network simulator	ns-2.31			
VANET mobility generator	Real trace	CityMob	SUMO	VanetMobiSim
number of nodes[3]	221			
map area size	$6500m \times 6500m$			
maximum speed[4]	$40.23\ km/h$			
distance between streets	-	$100m$	$100m$	-
downtown size	-	$2000m \times 2000m$	-	-
downtown speed (min.-max.)	-	$11 - 30\ km/h$	-	-
downtown probability	-	0.6	-	-
number of warning mode nodes	3			
warning packet size	$256B$			
normal packet size	$512B$			
packets sent by nodes	1 *per second*			
warning message priority	$AC3$			
normal message priority	$AC1$			
MAC/PHY	802.11p			
maximum transmission range	$250m$			

As shown, Freesim exhibits good software characteristics but is limited in other functions. SUMO, MOVE, STRAW and VanetMobiSim all have good software features and traffic model support. However, only VanetMobiSim provides excellent trace file support.

As for *Graphical User Interfaces* (GUIs), they are intuitive and user friendly. Figure 6.3 shows the GUIs of some VANET mobility generators, including our proposal.

6.4 Performance Comparison of Mobility Generators

In most VANET simulations, researchers working in safety applications evaluate the effectiveness and performance of their proposed *Warning Message Dissemination* (WMD) protocol. Such a protocol is viewed to be useful when an accident occurs. It can help to alleviate congestion and warn other vehicles about the accident. To evaluate the realism and effectiveness of existing VANET mobility generators, we performed the simulation of a generic WMD protocol on ns-2 using VanetMobiSim, CityMob, SUMO, and real traces. Real traces were obtained from real mobility data, as in the Cabspotting project [Cab09]. Table 6.3 shows the simulation parameters used. Note that we have included an 802.11p implementation into the ns-2 simulator.

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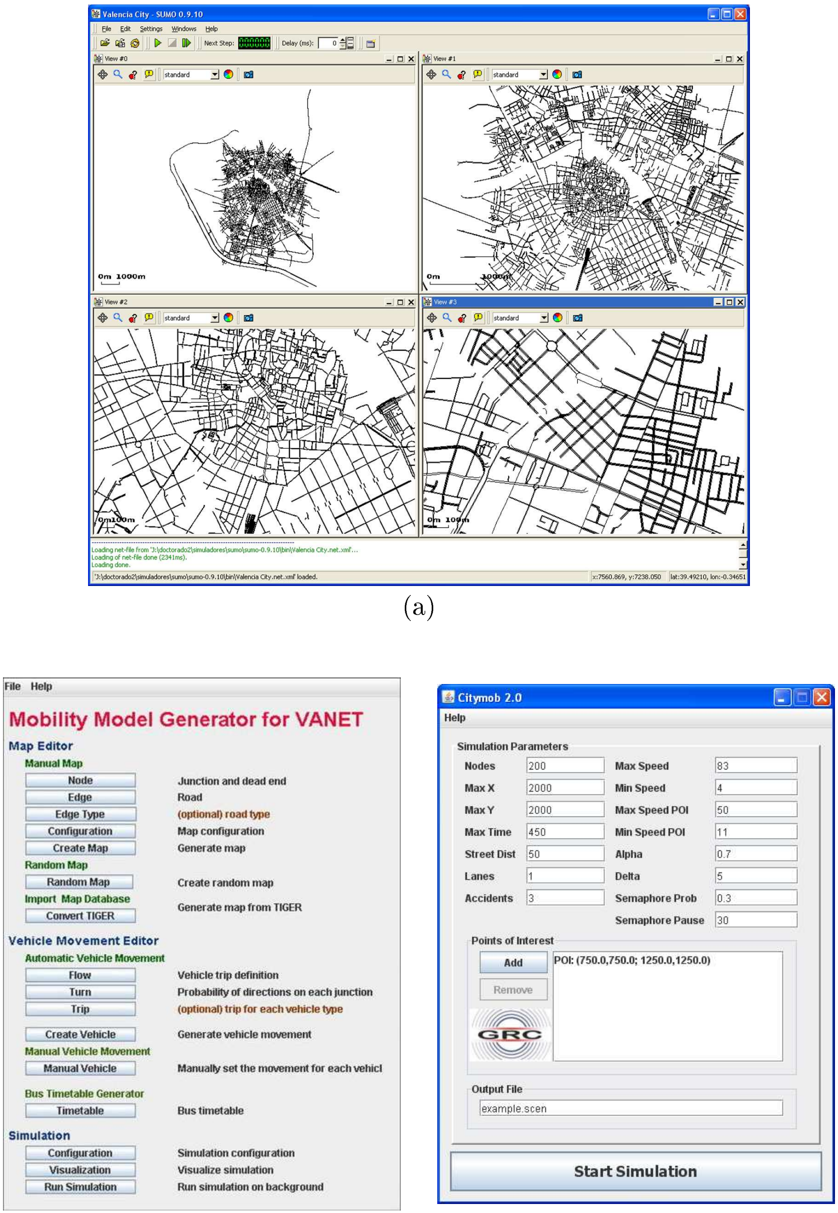
[3] Real trace had this number of vehicles.

[4] The maximum speed allowed in San Francisco.



```
Loading net-file from 'J:\doctorado2\simuladores\sumo\sumo-0.9.10\bin\Valencia City.net.xml'...
Loading of net-file done (2341ms).
Loading done.
'J:\doctorado2\simuladores\sumo\sumo-0.9.10\bin\Valencia City.net.xml' loaded.    x:7560.869, y:7238.050    lat:39.49210, lon:-0.34651
```

(a)

Mobility Model Generator for VANET

Map Editor

Manual Map

Node	Junction and dead end
Edge	Road
Edge Type	(optional) road type
Configuration	Map configuration
Create Map	Generate map

Random Map

Random Map	Create random map

Import Map Database

Convert TIGER	Generate map from TIGER

Vehicle Movement Editor

Automatic Vehicle Movement

Flow	Vehicle trip definition
Turn	Probability of directions on each junction
Trip	(optional) trip for each vehicle type
Create Vehicle	Generate vehicle movement

Manual Vehicle Movement

Manual Vehicle	Manually set the movement for each vehicl

Bus Timetable Generator

Timetable	Bus timetable

Simulation

Configuration	Simulation configuration
Visualization	Visualize simulation
Run Simulation	Run simulation on background

(b)

Simulation Parameters

Nodes	200	Max Speed	83
Max X	2000	Min Speed	4
Max Y	2000	Max Speed POI	50
Max Time	450	Min Speed POI	11
Street Dist	50	Alpha	0.7
Lanes	1	Delta	5
Accidents	3	Semaphore Prob	0.3
		Semaphore Pause	30

Points of Interest

POI: (750.0,750.0; 1250.0,1250.0)

Output File

example.scen

(c)

Figure 6.3: Graphical User Interfaces (GUIs) of (a) SUMO, (b) MOVE, and (c) CityMob v.2.

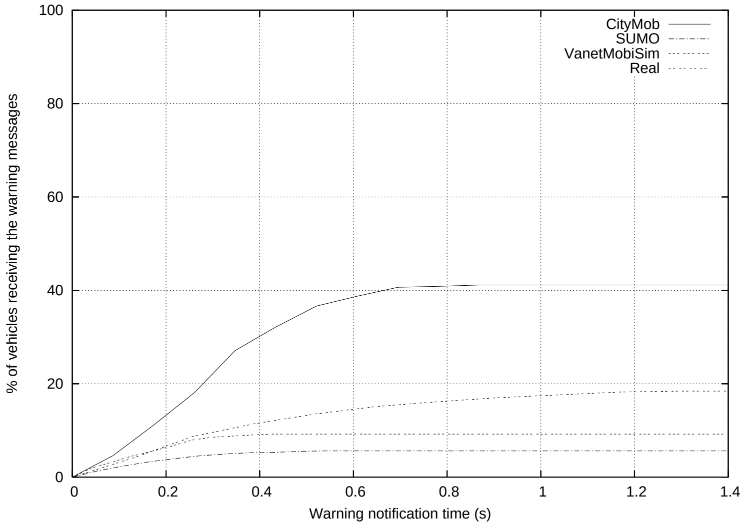


Figure 6.4: Cumulative histogram for the time evolution of disseminated warning messages using different mobility traces.

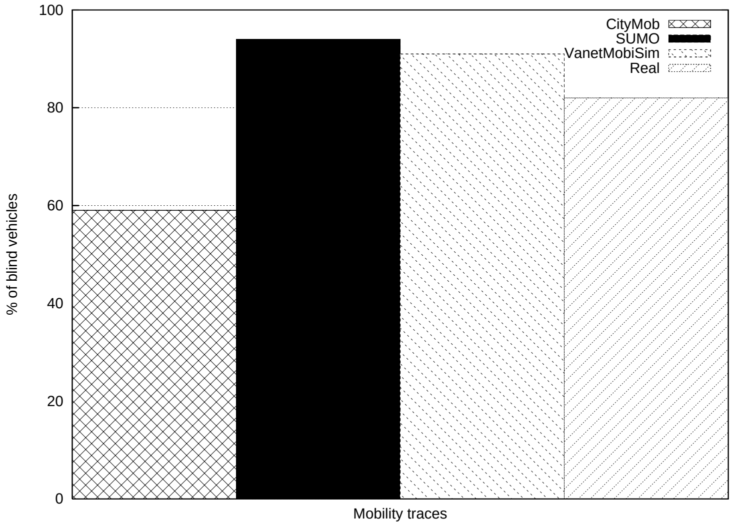
The performance parameters we measured include: (a) the percentage of blind vehicles, (b) the warning message notification time, and (c) the number of packets received per vehicle. The percentage of blind vehicles is the percentage of vehicles that do not receive the warning messages sent by the accident vehicle. The warning notification time is the time required by normal vehicles to receive the warning message.

As shown in Figure 6.4, the CityMob based mobility results in the shortest warning notification time, followed by Real, VanetMobiSim, and SUMO. In terms of percentage of blind vehicles, SUMO resulted in the largest percentage of blind vehicles (Figure 6.5a). Finally, in terms of number of packets received, CityMob allows obtaining the highest values, with VanetMobiSim and SUMO showing similar results.

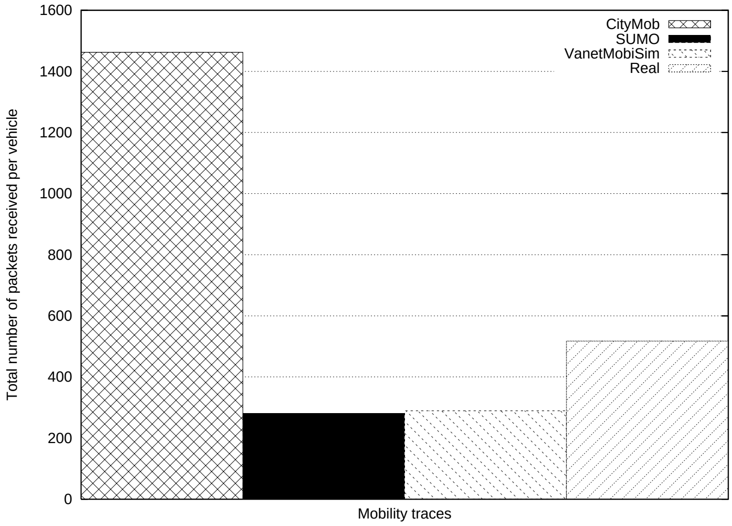
Our investigation shows that, when simulating the same WMD protocol with the same network simulator over different VANET mobility generators, different performance results will be obtained. Such deviations can make results unconvincing and inconclusive. So far, only VanetMobiSim produces results that closely resemble Real traces.

6.5 Summary

In this chapter we address the VANET mobility models issue. We introduced two different mobility generators specially designed for generating VANET urban mobility patterns. CityMob v.1 is a mobility pattern generator specially designed to investigate different mobility models in VANETs, and their impact on inter-vehicle



(a)



(b)

Figure 6.5: Results for: (a) percentage of blind vehicles, and (b) total number of packets received at each vehicle for the different mobility traces.

communications performance. CityMob creates urban mobility scenarios and simulates damaged cars using the network to send information to other vehicles, trying to prevent accidents or traffic jams. CityMob v.1 includes three different mobility models that combine a certain level of randomness, while trying to represent some realistic environments.

CityMob v.2 implements an enhanced version of the realistic *Downtown Model* (DM) which has the following capabilities: (a) multiple lanes in both directions for every street, (b) vehicle queues due to traffic jams, and (c) the possibility of having more than a downtown.

Additionally, in order to simulate real roadmaps, we proposed using openstreetmap.org to get the real map scenarios, and SUMO to generate the vehicles and their movements within these scenarios. This traffic simulator approach is also showing an increasing popularity as it allows to obtain a level of precision that cannot be reached by any synthetic model currently available.

In the future we will address the limitations that this environment presents since, although SUMO is a well-known traffic simulator, it sometimes does not model traffic density in a realistic way.

Chapter 7

Improved Radio Propagation Models for Vehicular Networks

Research in Vehicular Ad hoc Networks (VANETs) has found in simulation the most useful method to test new algorithms and techniques. However, some features such as using real topologies, radio signal absorption due to obstacles and channel access are rarely included, and therefore, results obtained are far from being realistic.

In this chapter we propose four different RPMs that increase the level of realism in simulations, thereby allowing us to obtain more accurate and meaningful results. These models are: (i) the Distance Attenuation Model (DAM), (ii) the Building Model (BM), (iii) the Building and Distance Attenuation Model (BDAM), and (iv) the Real Attenuation and Visibility Model (RAV). We evaluated these models and compared them with both the Two-ray Ground, and the Nakagami models implemented in ns-2.

7.1 Introduction

As shown in Section 4.4.2, we observe that the most widely used simulators, such as ns-2, Glomosim, QualNet and OPNET, do not accurately simulate the radio propagation model. They do not take into account the physical obstacles present in urban environments (mostly buildings). For example, the commonly used Two-ray ground radio propagation model ignores effects such as RF attenuation due to buildings and other obstacles. In ns-2 [FV00], it is assumed that signals have a perfect 250m radius range, which is overly optimistic for urban environments. Consequently, simulation results are unlikely to accurately reflect system performance in the real world.

In urban scenarios, and at the frequency of 5.9 GHz (i.e., the frequency band adopted by the 802.11p standard), radio signals are 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. In order to accurately simulate how radio signals propagate in urban scenarios, we must consider the effect of the signal attenuation due to distance, along with the effect of obstacles blocking the signal propagation. Therefore, to better reflect wireless signal propagation, both attenuation and visibility schemes should be taken into account.

When taking into account visibility schemes, the topology of the map used to constrain vehicle movement is very important. Using complex layouts implies more computational time, but the results obtained are much more accurate. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). Layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the results obtained are likely to be similar to those obtained in realistic environments. Our proposed schemes model radio signal propagation in a realistic way, taking into account both attenuation and visibility in real urban scenarios.

To the best of our knowledge, the impact of buildings or other obstacles (specifically on 802.11p-based VANETs) has not yet been studied. It is evident that urban obstacles, such as buildings, will act as barriers for radio signals. In this chapter, we propose four different *Radio Propagation Models* (RPMs) specifically designed for IEEE 802.11p-based VANETs. Furthermore, we study the impact of these models on communications performance.

This chapter is organized as follows: Section 7.2 presents our proposed radio propagation models. Simulation results are described in Section 7.3. Finally, Section 7.4 concludes this chapter.

7.2 Proposed Radio Propagation Models

In this section, we present four new *Radio Propagation Models* (RPMs) that allow better modeling of losses due to attenuation and obstacles.

7.2.1 Distance Attenuation Model (DAM)

The *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 we have two different possibilities: (i) use a very detailed analytical model that relates signal strength and noise at the receiver with BER and PER, and (ii) directly relate the BER or PER to distance under specific channel conditions. The latter, though more restrictive, allows us to simplify calculations and thus significantly reduce simulation run-time.

We had integrated the results presented in [TMSH07] into ns-2. We had also tested several monotonically decreasing functions for the curve fitting process and found that an optimum trade-off between accuracy and execution time could be achieved using a third order polynomial (see Equation 7.1):

$$PER(x) = ax^3 + bx^2 + cx + d \tag{7.1}$$

where PER is the Packet Error Rate and x is the Euclidean distance between vehicles. In particular, the values obtained through regression were:

(a, b, c, d) = (-4.367e-09, 8.686e-06, -5.523e-3, 1)

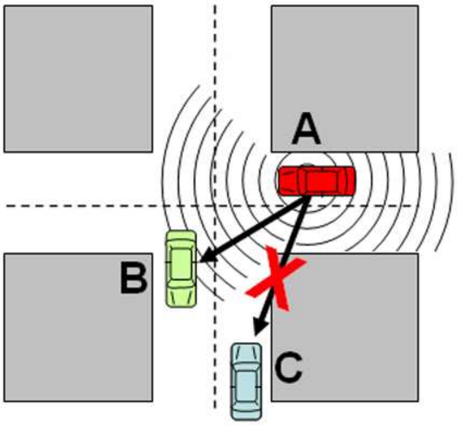


Figure 7.1: The Building Model: example scenario.

7.2.2 Building Model (BM)

The *Building Model* (BM) takes into consideration that, at a frequency of 5.9 GHz (i.e., the frequency band of the 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 the vehicles are in line-of-sight.

Figure 7.1 shows an example of this model. Dark rectangles represent buildings. In the Two-ray Ground and DAM models, vehicle C may receive the message from A. Nevertheless, with our 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.

7.2.3 Building and Distance Attenuation Model (BDAM)

The *Building and Distance Attenuation Model* (BDAM) combines both DAM and BM models. Now, communication will only be possible when the received signal is strong enough and vehicles are within line-of-sight.

BDAM can be considered more realistic than both DAM and BM, but it still has lack of realism since it is designed only for Manhattan-based scenarios. The Real Attenuation and Visibility model, presented in the next subsection, solves this problem.

7.2.4 Real Attenuation and Visibility (RAV) model

As shown in Sections 4.4.2 and 4.4.3, a wireless signal propagation model can be characterized by: (a) attenuation, and (b) visibility schemes. The combination of these schemes makes up our novel Radio propagation model, called *Realistic Attenuation and Visibility* (RAV) model.

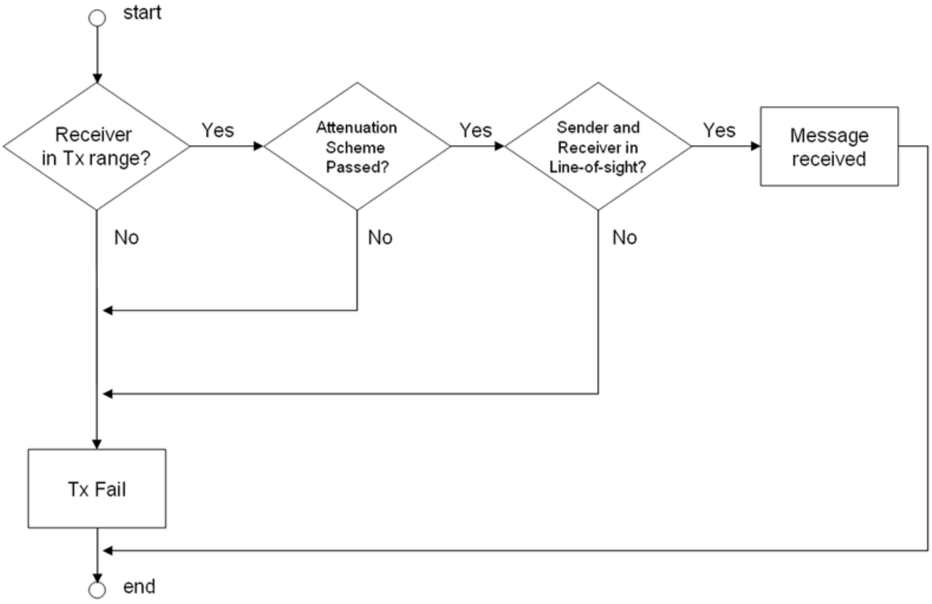


Figure 7.2: RAV model flowchart.

Figure 7.2 presents the summary flowchart of the process to determine if a packet is successfully received using our proposed model. As can be seen, each packet needs to overcome both the attenuation and the visibility restrictions of our RAV model to be considered correctly transmitted. Next, we elaborate further both the attenuation and the visibility schemes used in RAV.

7.2.4.1 RAV Attenuation Scheme

Our model implements signal attenuation due to the distance between vehicles as closely to reality as possible. In general, ns-2 offers deterministic RPMs, i.e., the selected function determines the maximum distance a packet could reach. If the receiver is within this range, the packet will be successfully received; on the contrary, if the distance is greater, it will be lost. In order to increase realism, we use a probabilistic approach to this problem to model packet losses due to collisions or other situations. So, we use a probability density function to determine the probability of a packet being successfully received at any given distance.

Our scheme is based on real data obtained from experiments in the 5.9 GHz frequency band using the IEEE 802.11a standard. The experiments consisted of several measurements of the *Packet Error Rate* (PER) when varying the distance between sender and receiver from zero up to 500 meters. In these experiments, we obtained an empirical maximum transmission range of 400 meters. Figures 7.3 and 7.4 show the car testbed, and the map of the physical location where the experiments took place, respectively.

Figure 7.3: Images of the experiment to determine the radio signal attenuation due to distance between vehicles.

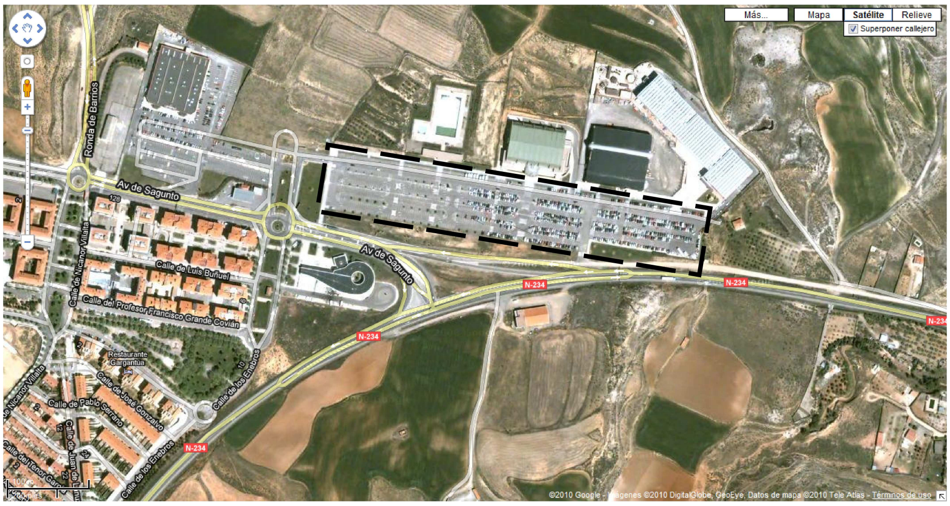


Figure 7.4: Image of the place where experiments of the 802.11a performance were made to determine the radio signal attenuation due to distance between vehicles (from Google Maps).

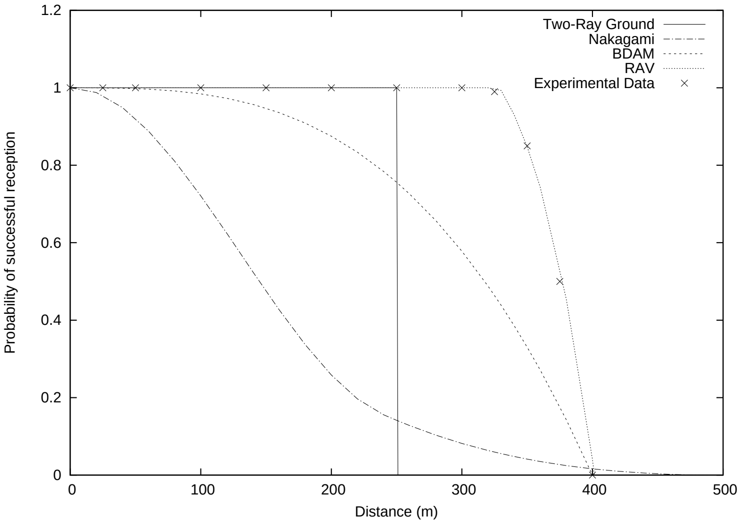


Figure 7.5: Comparison of different attenuation schemes. The RAV curve completely fits the obtained experimental data.

Using the collected data, we tested several monotonically decreasing functions for the curve fitting process and found that an acceptable trade-off between accuracy and execution time could be achieved using a fourth order polynomial:

$$PER(x) = ax^4 + bx^3 + cx^2 + dx + e, \tag{7.2}$$

where PER is the Packet Error Rate and x is the Euclidean distance between vehicles. In particular, the values obtained through regression were:

(a, b, c, d, e) = (–6.14e–10, 3.98e–7, –7.87e–5, 4.80e–3, 0.96)

With respect to other attenuation schemes, such as Two-Ray Ground and Nakagami, our scheme, instead of being theoretical, is obtained directly from experimental data. Moreover, instead of using a deterministic approach, we use a probabilistic function to model packet losses. Figure 7.5 shows the empirical data obtained in our experiments and our proposed attenuation curve compared with (a) Two-Ray Ground, (b) Nakagami [TMSH07] and (c) BDAM [MTC$^+$09b].

As can be seen, the only deterministic scheme is the Two-Ray Ground model, which is represented with a maximum transmission range of 250 meters. The Nakagami scheme has a slightly greater range, but the probability of successful transmission when the distance is above 200 meters is too low. Our proposed BDAM attenuation scheme behaves similarly to our RAV scheme, but for distances above 300 meters the probability of successfully transmitting is much higher using our RAV attenuation scheme.

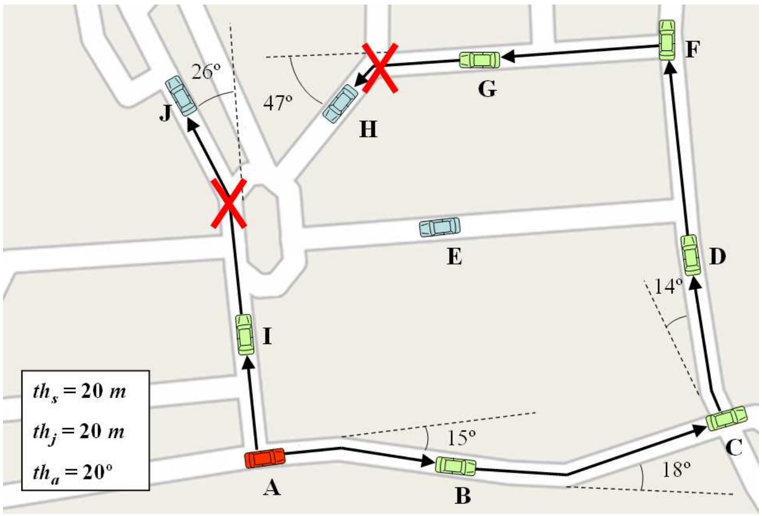


Figure 7.6: RAV visibility scheme: example scenario.

7.2.4.2 RAV Visibility Scheme

The main objective that a realistic visibility scheme should accomplish is to determine if there are obstacles between the sender and the receiver which interfere with the radio signal. In most cases, when using the 5.9 GHz frequency band (used by the 802.11p standard), buildings absorb radio waves and so communication is not possible. As shown in Section 7.2.3, the *Building and Distance Attenuation Model* (BDAM) [MTC$^+$09b] was designed to work only in Manhattan-style grid layouts, where simpler calculations were used to determine if two vehicles were in line-of-sight.

RAV goes one step forward by adapting the algorithm to support more complex and realistic layouts. Given a real reference map containing the street layout, our proposal basically states whether two different vehicles are in line-of-sight. Our street layouts are considered as undirected graphs where junctions are vertices and streets are edges that connect some pairs of vertices. We use a notation to define streets in which (x_s^1, y_s^1) is the initial vertex of the street s, and (x_s^2, y_s^2) represents its end vertex.

Figure 7.6 shows an example of the visibility scheme used in RAV, where vehicle (A) is trying to disseminate a message. In that case, and assuming that any vehicle receiving a message will rebroadcast it the first time, the result will be that some vehicles (B, C, D, F, G, and I) receive the message, while the others (E, H, and J) will never be reached by such message. The RAV visibility scheme considers that the radio signal can only propagate through the streets of the map, and thus the remaining parts of the map in an urban scenario are regarded as a set of buildings which prevents signal from propagating.

Instead of using the detailed mathematical model presented in Section 4.4.3.1, we use the following approach to reduce simulation time. The RAV visibility scheme calculates the angular difference between the streets where the vehicles are located, and then determines whether two vehicles are in line-of-sight using the following strategy:

- Two vehicles in the same street are always in line-of-sight. Using Equation 4.25, we consider that a vehicle is in a street (s) when the minimum distance (d_{min}) between its position ($P(x,y)$) and the line (r) formed as a extension of the street is less than a threshold (th_s). In addition, $P(x,y)$ must be included in the axis-oriented rectangle extended by th_s involving the street. As an example, in Figure 7.6, vehicles D and F are in the same street.

$$d_{min}(P(x,y),r) \leq th_s \wedge (x_s^1 - th_s) \leq x \leq (x_s^2 + th_s) \wedge (y_s^1 - th_s) \leq y \leq (y_s^2 + th_s) \tag{7.3}$$

- When a vehicle is in a junction (j), we consider that this vehicle may potentially communicate with all the vehicles present in the streets which start from the junction j, i.e., the vehicle is considered to be at the same time in all the neighbor streets. A threshold distance (th_j) is used to determine if a vehicle is close enough to a junction. As shown in Figure 7.6, vehicles A, C and F are close to a junction and, therefore, they are simultaneously in all the adjacent streets.

- Two vehicles in adjacent streets (labeled i and j) are in line-of-sight if the angular difference (α) between their streets is below a threshold th_a:

$$\begin{cases} \alpha'(i,j) = |atan2(y_i^2 - y_i^1, x_i^2 - x_i^1) - atan2(y_j^2 - y_j^1, x_j^2 - x_j^1)| \\ \alpha(i,j) = min(\alpha'(i,j), 2\pi - \alpha'(i,j)) < th_a \end{cases} \tag{7.4}$$

  This property can be extended if there is a series of linked streets between vehicles, and, for every street in the chain, the angular difference with the rest of streets is less than th_a (see Equation 7.5). In Figure 7.6, we have chosen $th_a = 20°$ (≈ 0.349 radians).

$$\forall i,j : in\_chain(i) \wedge in\_chain(j) \wedge i \neq j \Rightarrow \alpha(i,j) < th_a \tag{7.5}$$

Figure 7.7 schematically shows the three different conditions to consider that two vehicles are in line-of-sight in our RAV visibility scheme. Notice that the RAV visibility scheme only determines if there are obstacles (i.e. building which could block signal propagation) between sender and receiver. Actual success in communicating also depends on the distance between them, and on the attenuation scheme used.

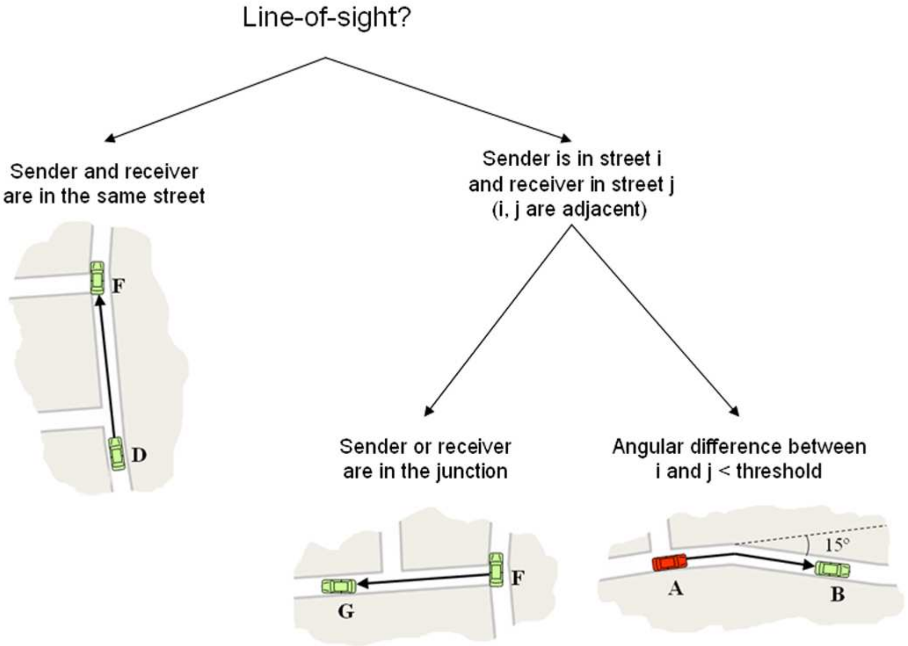


Figure 7.7: RAV: line-of-sight algorithm conditions.

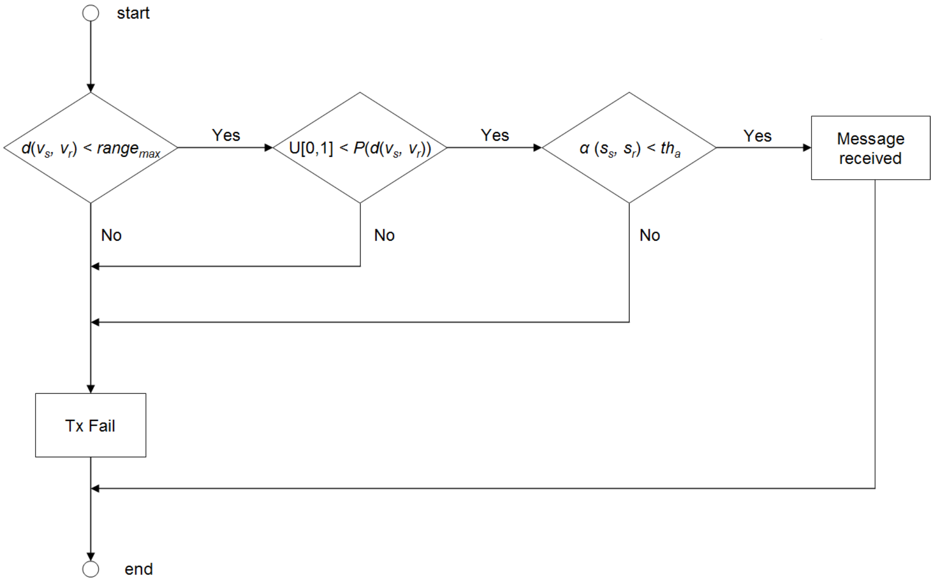


Figure 7.8: RAV model flowchart completed with formulas for the different schemes.

7.2.4.3 Summary of RAV operation

Figure 7.8 shows a flowchart with the specific conditions used to determine if a packet is successfully received using our proposed model. v_s and v_r represent the sender and the receiver vehicles, respectively. The distance between both vehicles is represented by $d(v_r, v_s)$, and $P\left(d(v_r, v_s)\right)$ indicates the probability of successful reception in an obstacle-free environment for that distance (attenuation scheme). The streets where v_s and v_r are located are shown as s_s and s_r.

7.3 Simulation Results

In this section, we evaluate the impact of our proposed RPMs presented in section 7.2 on the performance of a VANET message dissemination protocol.

We divided the simulation results into two different parts: (i) a comparison between the Manhattan-based RPMs (DAM, BM, and BDAM) (see Section 7.3.1), and (ii) a detailed evaluation of the RAV model (see Section 7.3.2).

7.3.1 Manhattan-based RPMs Evaluation

To perform the evaluation, we first determine a set of basic results using a reference scenario (see Table 7.1). Then, by using a wide variety of scenarios, and by varying the selected parameters one at a time, we performed a detailed analysis to illustrate the impact of the realistic RPMs introduced.

Table 7.1: Parameter values for the Manhattan-based reference scenario

Parameter	**Value**
number of vehicles	100
maximum speed	$23\ m/sec. \approx\ 83\ km/h$
simulated area	$2000m \times 2000m$
building size	$20m$
distance between streets	$50m$
number of warning mode vehicles	3
downtown size	$500m \times 500m$
downtown speed (min.-max.)	$3 - 14\ m/sec. \approx\ 11 - 50\ km/h$
downtown probability	0.7
warning packet size	$256B$
normal packet size	$512B$
packets sent by vehicles	1 *per second*
warning message priority	$AC3$
normal message priority	$AC1$

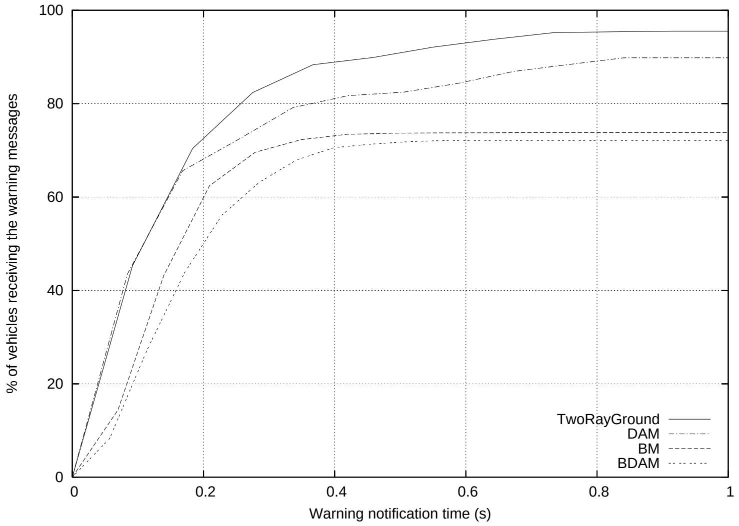


Figure 7.9: Cumulative histogram for the time evolution of disseminated warning messages for the different RPMs (reference scenario).

The results shown in this section represent an average over various executions with different randomly generated mobility scenarios and with three warning mode vehicles placed randomly. Since the performance results are highly related to the scenarios, and due to the random nature of the mobility model used, we repeated the simulations to obtain reasonable confidence intervals. All results present a maximum error of 10% with a degree of confidence of 90%.

7.3.1.1 Reference Scenario for the proposed Manhattan-based RPMs

Figure 7.9 depicts the warning notification time for the different Manhattan-based RPMs in the reference scenario. As shown, information does not reach all vehicles, but within 0.26 seconds about 60% of the vehicles receive the warning message in the worst case (BDAM). The propagation process needs more time to complete for Two-ray Ground and DAM models, since these models are less restrictive and the number of possible hops is greater. Although, in the BM and BDAM models, the propagation ends sooner, fewer vehicles are informed since warning messages are blocked by buildings. The BDAM model reveals the presence of blind vehicles more accurately than other RPMs. The number of packets received per vehicle is 77.34, 47.51, 20.78 and 16.00 for the Two-ray Ground, DAM, BM and BDAM models, respectively. The number of packets received decreases considerably since signal propagation encounters more restrictions.

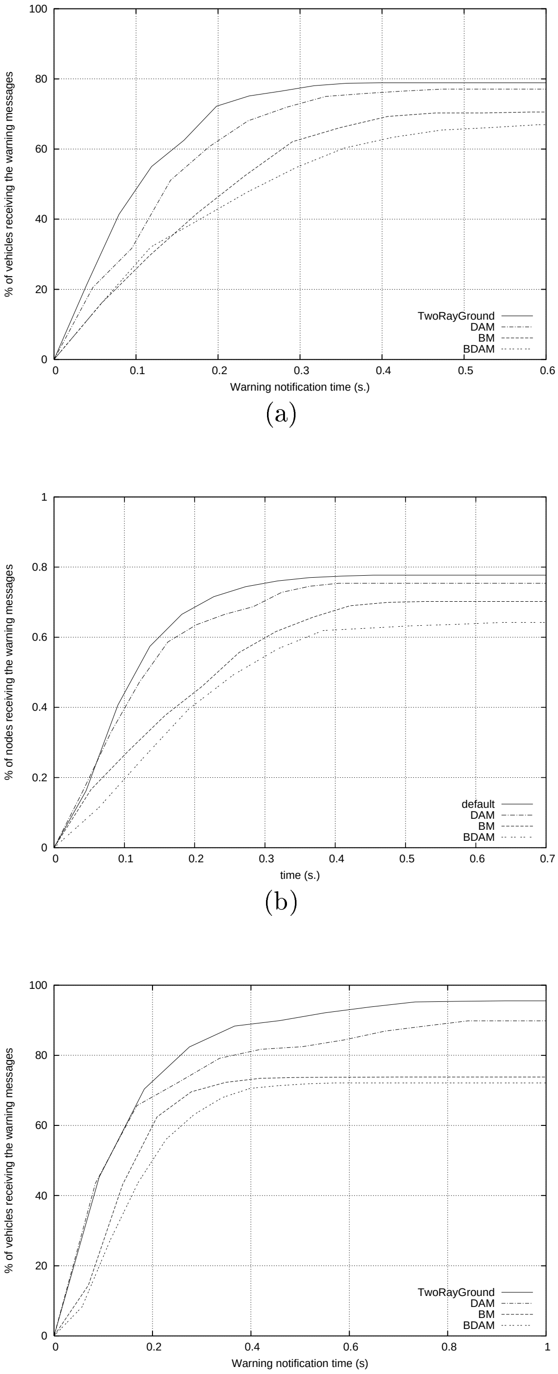
We observed that BM and BDAM performance is similar in this scenario and, therefore, dissemination is more affected by the presence of buildings rather than by the signal attenuation due to distance.

7.3.1.2 Varying the Number of Vehicles

Figures 7.10, 7.11 and 7.12 show the simulation results when varying the number of vehicles while maintaining the rest of parameters unaltered. We performed simulations for 25, 50, 100 (reference scenario), 150 and 200 vehicles.

As shown, the warning notification time and the percentage of blind vehicles highly depends on the vehicle density (see Figures 7.10, 7.11 and 7.12). With a small number of vehicles, i.e., when the vehicle density is low, the behavior of the RPMs is similar since vehicles are mainly concentrated in the downtown. The warning message propagation is faster for the Two-ray Ground and DAM models. Nevertheless, with a large number of vehicles, i.e. when the vehicle density is higher, there are no blind vehicles for both Two-ray Ground and DAM models. For the BM and BDAM models, warning information does not reach all vehicles since these two RPMs are more restrictive. Obviously, the propagation process needs more time to complete when there are more vehicles, but the difference is almost negligible.

RPMs can also affect the number of packets received per vehicle (see Figure 7.12b). In BM and BDAM models, the number of packets received decreases considerably since signal propagation encounters more restrictions. We observe that in both BM and BDAM models, the number of warning message packets received does not depend on vehicle density.

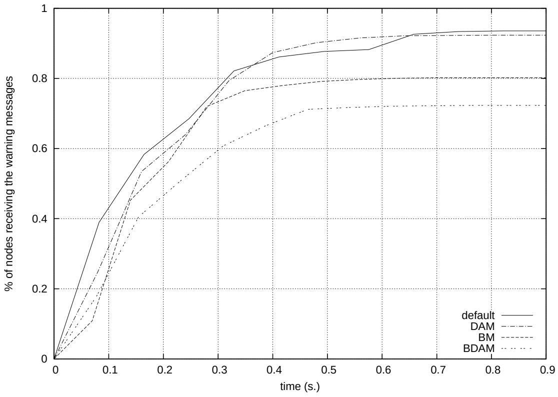


(a)

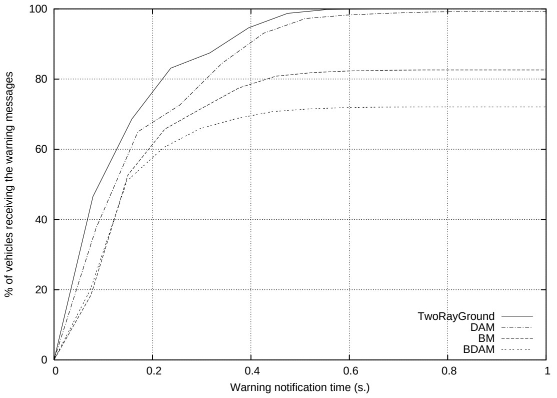
(b)

(c)

Figure 7.10: Cumulative histogram for the time evolution of disseminated warning messages when varying the number of vehicles (a) 25, (b) 50, and (c) 100.

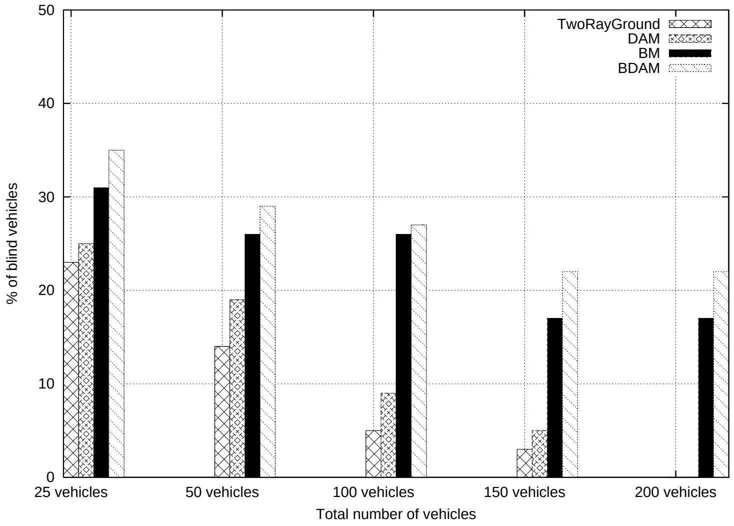


(d)

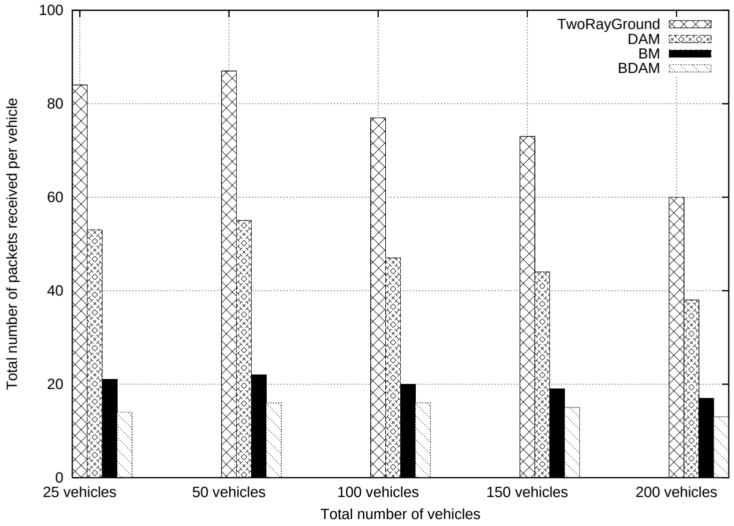


(e)

Figure 7.11: Cumulative histogram for the time evolution of disseminated warning messages when varying the number of vehicles (cont.) (d) 150, and (e) 200.



(a)



(b)

Figure 7.12: (a) Percentage of blind vehicles vs. number of vehicles, and (b) total number of packets received at each vehicle vs. number of vehicles.

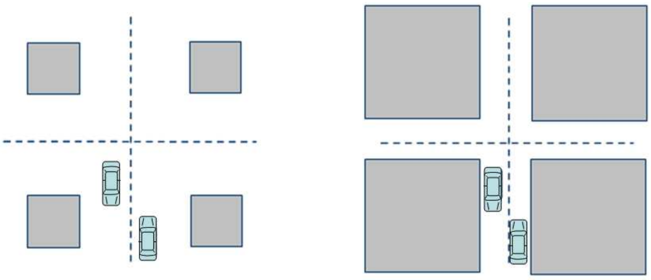


Figure 7.13: Effect of varying the building size.

7.3.1.3 Varying the Building Size

In this section, we present the simulation results when varying the building size while maintaining other parameters unaltered. We used building sizes of 10m, 20m (reference scenario), 30m and 40m. Figure 7.13 illustrates the effect of varying the building size. Note that, in our proposed urban scenario, the effect of increasing the building size is exactly the same than reducing the road width.

As expected, Figures 7.14 and 7.15 show that the building size does not affect the Two-ray Ground and DAM models. This is expected since these RPMs do not take into account the presence of buildings. The warning notification time is slightly lower for the BM and BDAM models when the building size is smaller, meaning that wider streets make communication easier and faster.

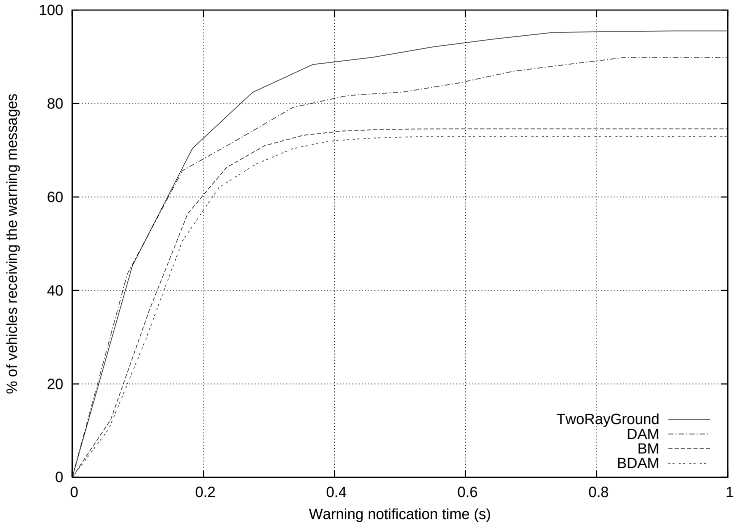
The percentage of blind vehicles increases and the number of packets received (see Figures 7.15a and 7.15b) decreases initially when the buildings are considered for both BM and BDAM models.

The percentage of blind vehicles increases when the building size increases (from 10m to 40m: +12.27% for BM and +10.59% for BDAM). Note that the number of packets received decreases when the building size increases (from 10m to 40m: −18.03% for BM and −23.36% for BDAM). This is because buildings block the dissemination of warning messages.

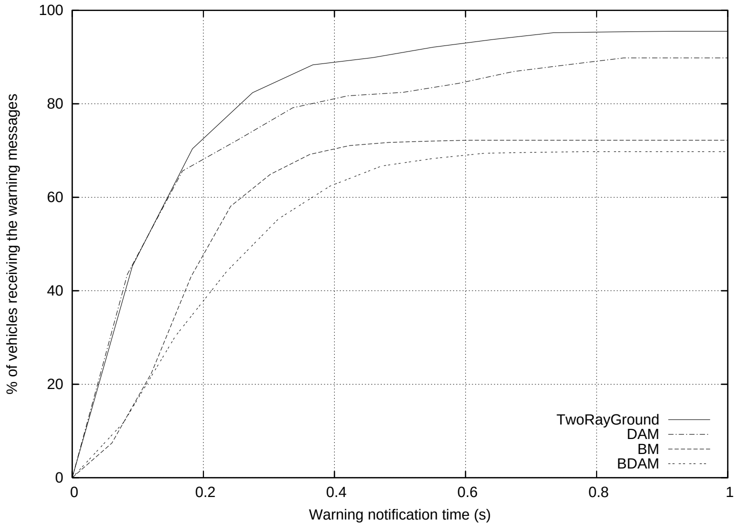
7.3.1.4 Overall Summary for the proposed Manhattan-based RPMs

In table 7.2 we present a summary of the average performance results obtained when simulating with different proposed Manhattan-based RPMs. The data presented for the warning notification time is the time necessary to inform at least 60% of vehicles in the simulated scenario. As shown, when the model is more restrictive, more time is needed to reach the same percentage of vehicles, and the percentage of blind vehicles increases. Nevertheless, the average number of packets received per vehicle decreases considerably.

The results show that using more realistic models tends to reduce protocol performance, allowing us to better understand the impact of buildings and obstacles along the road on car-to-car communications.

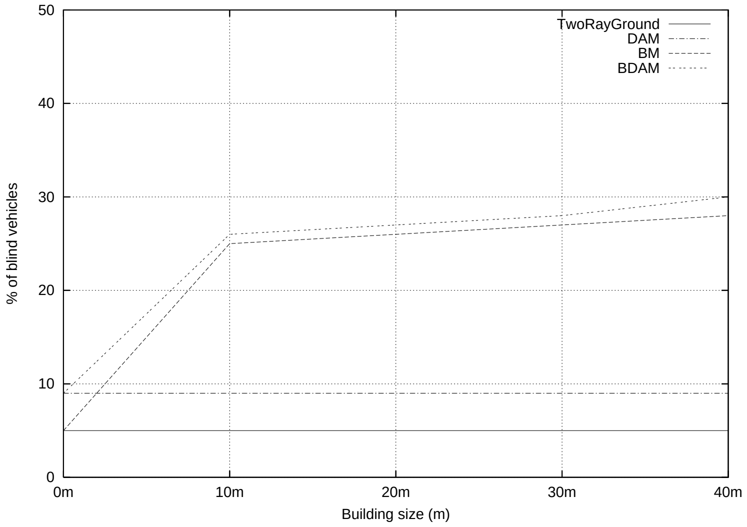


(a)

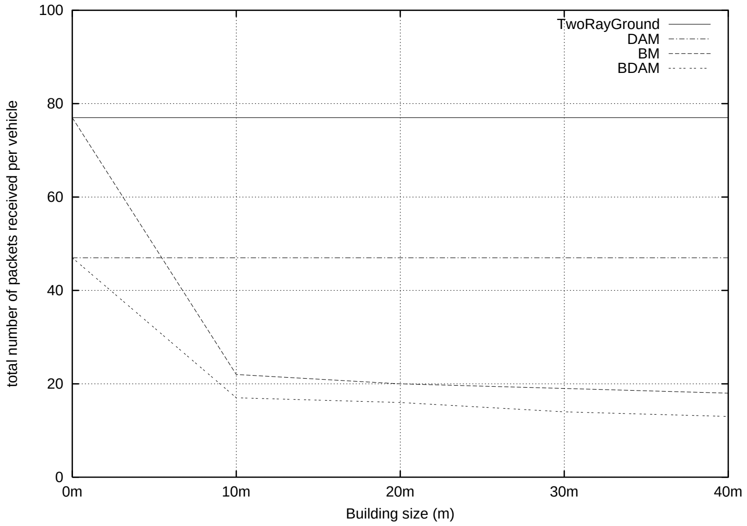


(b)

Figure 7.14: Cumulative histogram for the time evolution of disseminated warning messages when varying the building size (a) 10m, and (b) 40m.



(a)



(b)

Figure 7.15: (a) Percentage of blind vehicles, and (b) number of packets received when varying the building size.

Table 7.2: Performance under different Manhattan-based RPMs

Performance	**Schemes**			
	Two-ray	**DAM**	**BM**	**BDAM**
Warning notification time (s)	0.15	0.17	0.23	0.29
% of blind vehicles detected	9.59	12.03	23.82	27.43
Number of packets received	76.58	47.84	20.23	15.17

Table 7.3: Parameter values for the real roadmap simulations

Parameter	**Value**
number of vehicles	$50, 100, 200, 300, 400$
maximum speed	$23\ m/sec. \approx\ 83\ km/h$
simulated area	$2000m \times 2000m$
number of warning mode vehicles	3
warning packet size	$256B$
normal packet size	$512B$
packets sent by vehicles	1 *per second*
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
maximum transmission range	$400m$
RAV th_s	$20m$
RAV th_j	$20m$
RAV th_a	$15°$
mobility generator	SUMO [KR07]

7.3.2 RAV Model Evaluation

We now evaluate the impact of the RAV model presented in section 7.2.4 on the performance of a Warning Message Dissemination application, typically used in VANETs. Concerning the simulated scenario, we have selected three different real cities representing different environments (see Figure 7.16). The city of Teruel (Spain) is an example of a town with low density of streets and junctions, arranged in a complex layout different from typical Manhattan-grid layouts. The city of Valencia (Spain) represents a city with an extremely high density of streets and junctions. The city of Manhattan (KS, USA) has a very regular street layout where the simulations should have a very similar behavior compared to simulations performed using synthetic Manhattan-grid layouts. Table 7.3 shows the most representative parameter values used in our simulations.

7.3.2.1 Evaluating the impact of the RAV model versus other existing radio propagation models

We test both attenuation and visibility schemes independently, i.e., we perform simulations by varying the attenuation scheme using the same visibility scheme, and vice versa. Our intention is to evaluate the cross-effect that different schemes

(a) (b)

(c) (d)

(e) (f)

Figure 7.16: Scenarios used in our simulations: (a) fragment of the city of Teruel (Spain) obtained from OpenStreetMap, and (b) the same fragment as a street graph in SUMO. (c) Fragment of the city of Valencia (Spain) obtained from OpenStreetMap, and (d) the same fragment as a street graph in SUMO. (e) Fragment of the city of Manhattan (KS) obtained from OpenStreetMap, and (f) the same fragment as a street graph in SUMO.

will have over the network performance and to measure the differences when we increase the level of realism of the simulations. In this subsection, the size of all the scenarios is 4 km^2, and the network density is 50 vehicles/km^2.

Warning notification time

Figure 7.17 represents the less realistic scenario in which we use an obstacle-free environment (default ns-2 visibility scheme) and the vehicle movements are constrained to a synthetic Manhattan-grid scenario. As shown, in all the simulations 100% of the vehicles received the warning messages since signal propagates without being interfered by buildings. When using Two-Ray Ground, the system required 0.7 seconds to reach all vehicles; however, when using our proposed RAV attenuation scheme (obtained from experimental data), the warning notification time is reduced to 0.2 seconds.

Figure 7.18 shows the results obtained when a more realistic visibility scheme is used. The scenario is the same as in Figure 7.17, but now buildings are considered as obstacles which interfere with radio signal, i.e., we are using the visibility scheme for synthetic Manhattan scenarios presented in Section 4.4.3. In this case, not all attenuation schemes are able to reach 100% of the vehicles. In fact, only when using the proposed RAV and BDAM schemes are all the vehicles informed about the dangerous situation. If we use the Nakagami attenuation scheme, only 50% of the vehicles are informed on average, a value that increases to 90% with the Two-Ray Ground scheme. It is also noticeable that, during the first 0.5 seconds of the process, all the schemes present a similar behavior.

Results in Figure 7.19 are obtained using the real map from Figure 7.16 (d) as the simulation topology. Since the RAV visibility scheme is most suitable for this environment, hence, all simulations were run using this scheme. If we use Two-Ray Ground, only 50% of the vehicles are aware of the dangerous situation on average, and it increases to almost 60% with the Nakagami fading model. RAV and BDAM attenuation schemes show a similar behavior; in both cases, warning messages reach around 70% of the vehicles, and the time required to inform at least 50% of the vehicles is the lowest (less than 0.25 seconds).

In order to better observe the effects of the different visibility schemes, Figure 7.20 shows the results obtained using our proposed RAV attenuation scheme in the different scenarios previously used. If we do not account for obstacles (ns-2 current visibility model), warning messages rapidly reach 100% of the vehicles because signal propagation suffers from few constraints.

As expected, there are more blind vehicles using a realistic topology than using a Manhattan layout. However, the warning notification time is lower (60% of vehicles are informed in only 0.3 seconds), and so the propagation process needs less time to complete (0.6 seconds).

The higher percentage of blind vehicles in a real scenario is due to the complex topology used, which makes it harder to reach specific areas of the map, while in the Manhattan layout streets are straight and signal reaches longer distances, making it easier to discover new vehicles. As for the warning notification time, since in our real map there are many more junctions, the probability of a vehicle to be near a junction is higher, making the propagation of warning messages to the all the adjacent streets faster.

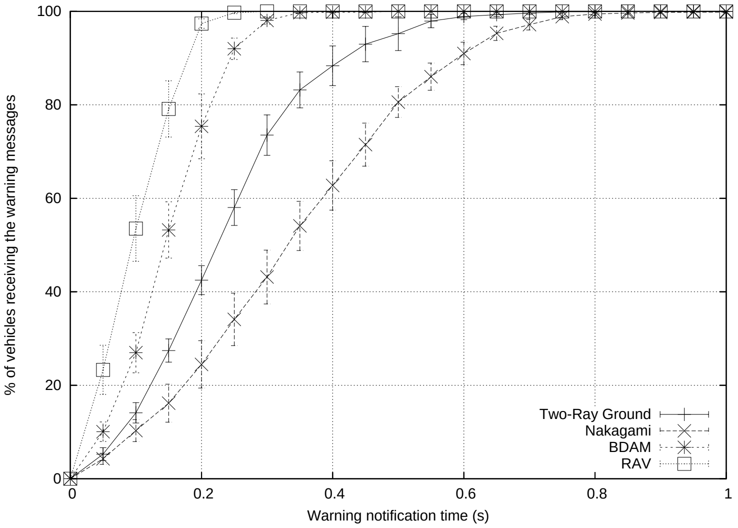


Figure 7.17: Warning notification time when varying the attenuation scheme without accounting for obstacles (buildings) in a synthetic Manhattan scenario.

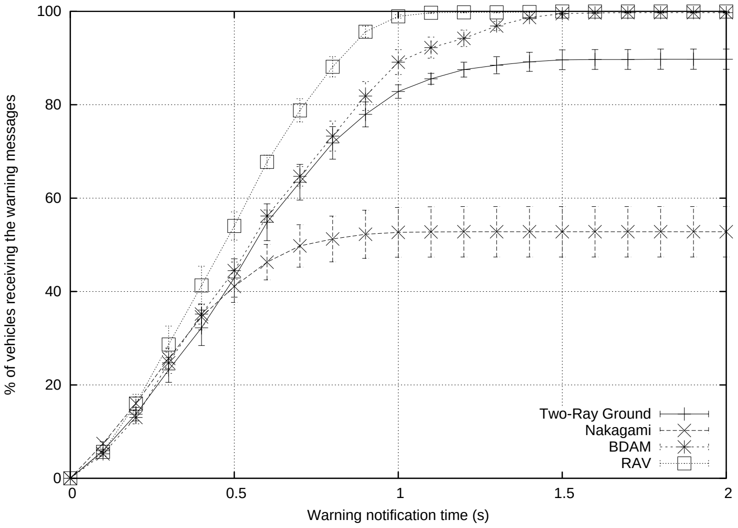


Figure 7.18: Warning notification time when varying the attenuation scheme with obstacles in a synthetic Manhattan scenario.

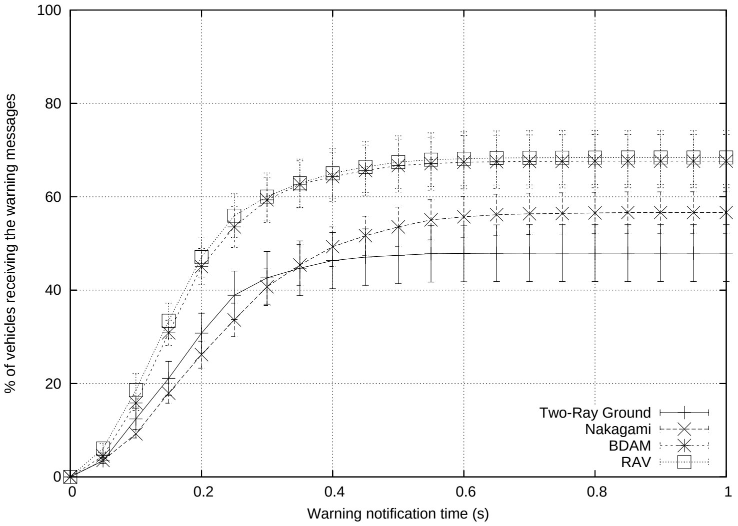


Figure 7.19: Warning notification time when varying the attenuation scheme with obstacles and using a real map layout (Valencia).

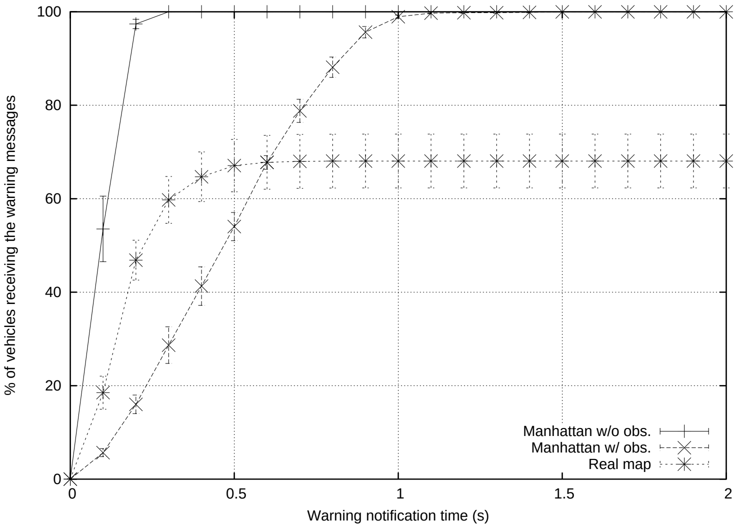


Figure 7.20: Warning notification time when using the realistic attenuation scheme and varying the visibility/layout schemes.

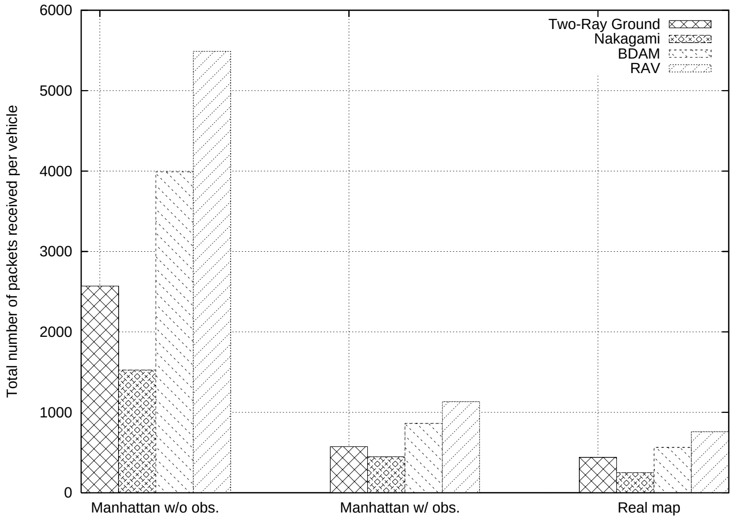


Figure 7.21: Average number of messages received per vehicle when varying the visibility and attenuation scheme.

Received messages

Figure 7.21 shows the effects of the attenuation and visibility schemes on the average number of messages received per vehicle. As can be seen, in all the simulated scenarios, using our proposed RAV attenuation scheme yields higher number of packets as the simulated distance reachable by messages is also the highest. The Nakagami scheme presents the lesser number of packets due to the low probability of successful transmissions when the distance between sender and receiver exceeds 200 meters.

If we vary the visibility scheme, the number of received messages is reduced drastically as we use more realistic schemes. Using the RAV attenuation scheme, in an obstacle-free environment, each node receives more than 5000 messages, while in a real map layout in which buildings interfere with radio signal (RAV visibility scheme) the number of received messages is below 800 messages. Results obtained when using a synthetic Manhattan scenario are similar in shape to those obtained in a real map, but the collected data for all attenuation schemes are about 50% higher.

7.3.2.2 Evaluating the impact of vehicle density and simulation scenario

We will now test the impact of different simulation environments and different vehicle densities in the effectiveness of the warning message dissemination using the RAV model. The number of vehicles involved in each simulation takes different values: 50 (12.5 vehicles/km^2), 100 (25 vehicles/km^2), 200 (50 vehicles/km^2), 300

(75 vehicles/km^2), and 400 (100 vehicles/km^2); we use the real maps presented in Figure 7.16.

Warning notification time

In Figure 7.22, the simulation scenario used is the map of the city of Teruel. As shown, increasing vehicle density allows to reach a greater number of vehicles in the scenario. In all cases, the propagation process was completed in less than 0.5 seconds, although with higher density this process is faster (only 0.2 seconds to inform 60% of the vehicles). With a small vehicle density (12.5 nodes/km^2), about 25% of the rest of the vehicles are informed of the dangerous situation, which indicates that only the closest vehicles get the warning messages. It is very noticeable that the percentage of vehicles receiving warning messages is similar for all simulations with more than 25 vehicles/km^2; in fact, simulating 300 vehicles achieves better average results than simulating 400 vehicles. This effect arises when the maximum propagation capacity of the scenario is reached, and allows us to identify the presence of the broadcast storm problem when vehicle density exceeds 75 vehicles/km^2.

Figure 7.23 represents the results attained using the city of Valencia as the map layout for vehicle movement. This layout has much more streets than the previous one, which reduces the probability of having many vehicles in the same street, thus reducing the broadcast storm problem when using the map of Teruel. As shown, with 100 vehicles in the simulations, warning messages reach 60% of the vehicles, and this percentage increases up to 90% with 300 and 400 vehicles. The propagation process now needs around 0.6 seconds to finish.

Finally, Figure 7.24 shows how the propagation process develops in the map from the city of Manhattan. The results are similar to those attained in the map of Valencia, but now the signal propagates more easily through the straight streets, thus increasing the number of receiving nodes for all vehicle densities. For densities above 50 vehicles/km^2, at least 80% of the vehicles are informed about the dangerous situation. The propagation process is the longest of all scenarios, as it needs 0.8 seconds to complete for some configurations.

To better analyze the effect of the network layout, we present the previous results according to the network density. Figure 7.25 shows the warning notification times obtained when simulating the same vehicle density and varying the simulation scenario. When using 50 nodes, the street layout is not really decisive in terms of both the number of informed vehicles and the time required to complete the process. With low densities, the system is able to inform at least 30% of the vehicles in all cases. As we increase the vehicle density, the differences are more noticeable. With 100 nodes, the average number of receiving vehicles varies within a 20% interval; worst results are achieved using the map of Teruel and the best results with the map of Manhattan. Using 200 nodes, we get a situation where the different confidence intervals are not overlapped, proving that the performance of our dissemination scheme is really dependent on the selected map layout. With densities above 50 vehicles/km^2, the differences between using the map of Valencia or the map of Manhattan become smaller, while the performance attained with the map of Teruel is quite similar.

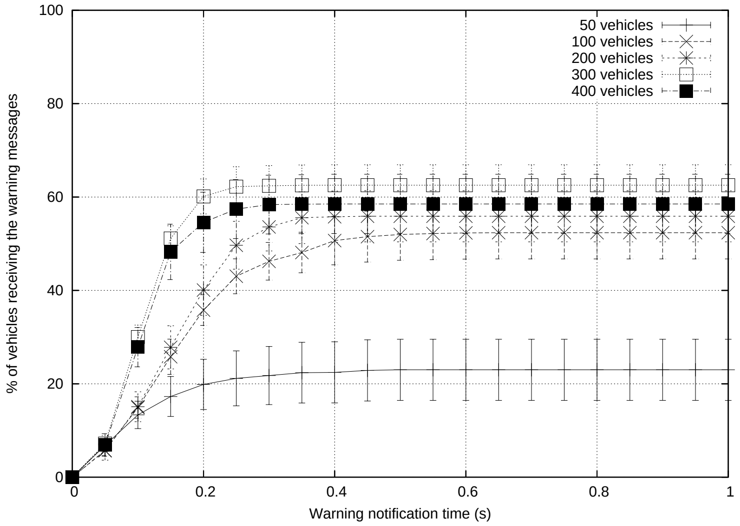


Figure 7.22: Warning notification time when varying the vehicle density in the map of Teruel.

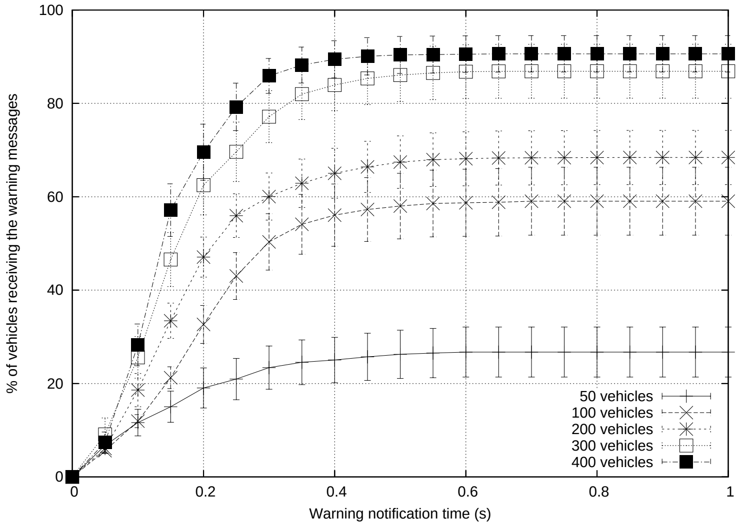


Figure 7.23: Warning notification time when varying the vehicle density in the map of Valencia.

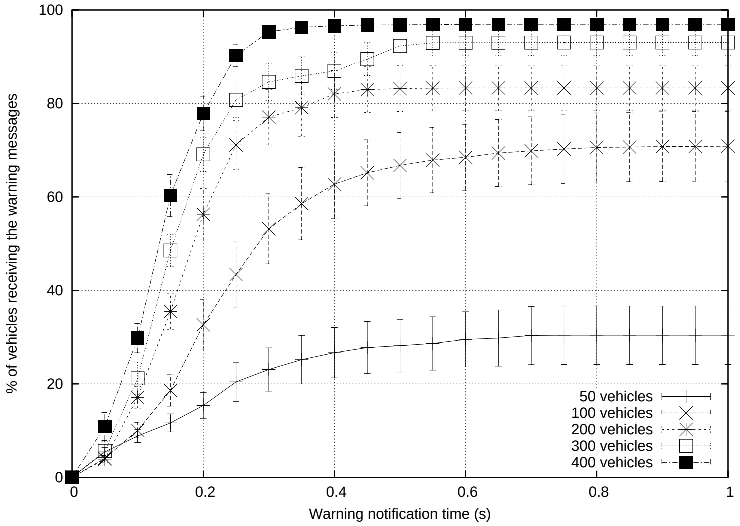
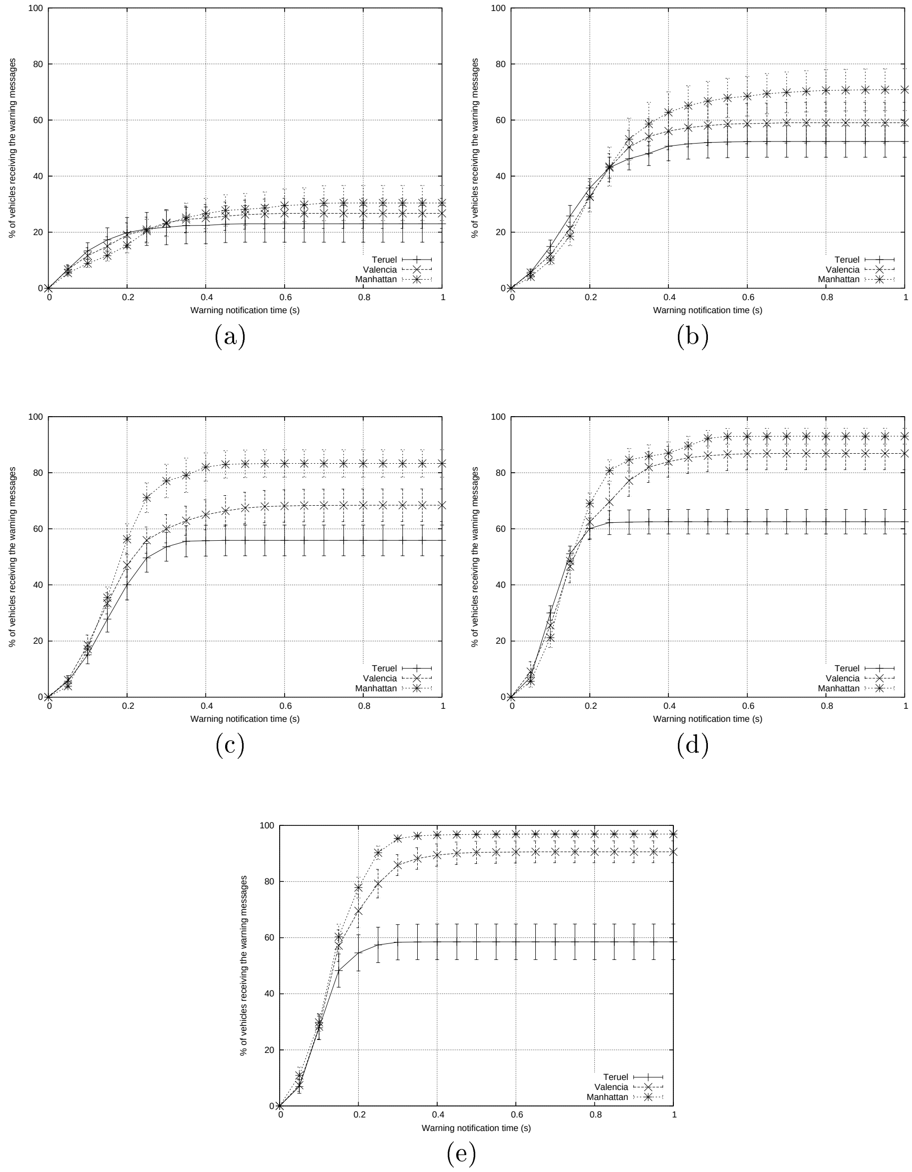


Figure 7.24: Warning notification time when varying the vehicle density in the map of Manhattan.

We can also observe that confidence intervals are usually smaller in a Manhattan layout in any configuration using more than 100 vehicles, proving that simulations performed with more regular layouts yield lesser variability in the obtained results. Teruel is the only city in which the confidence intervals grow, passing from 300 vehicles to 400 vehicles, due to the severe channel contention problems that arise when vehicle density becomes too high for the scenario.

Received messages

We now focus on the effects of the map used on the average number of messages received per node when varying the vehicle density. As shown in Figure 7.26, when the number of vehicles is 200 or below, the simulations using the three different scenarios have a similar behavior. This means that, in a sparsely connected vehicular network where the market penetration rate of wireless on-board devices is relatively low, warning message dissemination works with a noticeable performance in terms of informed vehicles and messages received per vehicle. However, when increasing vehicle density, the efficiency of the scheme depends greatly on the selected environment. Using an environment with a small street density like the city of Teruel leads to an excessive channel contention with 300 and 400 vehicles (75 and 100 vehicles/km^2, respectively). In Valencia, this problem is not so noticeable due to the higher number of streets, which impedes the signal from reaching as many vehicles, and thus reducing the probability of having two vehicles in line-of-sight. In fact, when using the map of Valencia, the number of received messages per node is almost the same using 300 and 400 vehicles. Finally, with a Manhattan scenario, we get similar results for 300 nodes with respect to the map



(a) (b) (c) (d) (e)

Figure 7.25: Warning notification time when varying the simulation scenario using (a) 50 vehicles, (b) 100 vehicles, (c) 200 vehicles, (d) 300 vehicles, and (e) 400 vehicles.

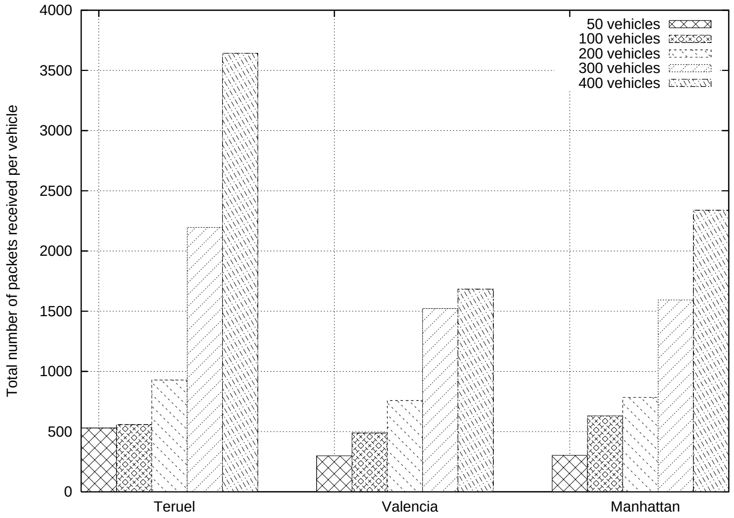


Figure 7.26: Average number of messages received per vehicle when varying the simulation scenario and the vehicle density.

of Valencia, although increasing vehicle density to 100 vehicles/km^2 (400 nodes) greatly increases the number of packets received.

7.4 Summary

In vehicular communications, an important effect experienced by wireless signals is the loss of power density as signals propagate through a specific environment specially in urban scenarios. In this chapter, we assessed the impact of having realistic radio propagation models on the performance of warning message dissemination in VANETs. We introduced four different RPMs: (i) DAM, (ii) BM, (iii) BDAM, and (iv) RAV. These models allow researchers to increase the level of realism of their VANET simulations.

Previous attenuation schemes were too restrictive in terms of maximum transmission range. Our experiments show that the radio signals generated by of-the-shelf IEEE 802.11a wireless cards, which use same band as 802.11p ones, have a reachability of about 400 meters, instead of 250 meters (ns-2 default transmission range).

Our RAV model allows obtaining better simulation results in terms of warning notification time and percentage of blind vehicles. As for visibility schemes, many research works do not consider the effect of buildings in their radio signal propagation model, or their models use very simplistic layouts. When using more realistic scenarios, we see that the percentage of blind nodes obtained with simple layouts is too optimistic. The proposed RAV model allows researchers to simulate real map layouts, allowing them to obtain more accurate results.

Chapter 8

Efficient Message Dissemination in Vehicular Networks

In urban wireless vehicular environments, an accident can cause many vehicles to send warning messages in order to warn nearby vehicles, and all vehicles within the transmission range will receive the broadcast transmissions and rebroadcast these messages (see Figure 8.1). Hence, a broadcast storm (serious redundancy, contention and massive packet collisions due to simultaneous forwarding) will occur. This effect must be reduced [TNCS02] to improve the performance of safety applications.

In the past, several approaches have been proposed to solve the broadcast storm problem in wireless networks such as *Mobile ad hoc Networks* (MANETs) and *Wireless Sensor Networks* (WSNs). They include counter-based, distance-based, location-based, cluster-based, and probabilistic schemes. In this chapter we present our novel *Street Broadcast Reduction* (SBR) protocol, a novel scheme that mitigates the broadcast storm problem in VANETs. SBR also reduces the warning message notification time and increases the number of vehicles that are informed about the alert. Simulation results in high density urban scenarios using the improvements presented in previous chapters show that, when SBR is combined with the location-based scheme, it outperforms other solutions by accounting for obstacles, thus providing a lower percentage of blind vehicles and drastically alleviating the broadcast storm problem.

8.1 Introduction

Although several schemes has been previously proposed to mitigate the well-known broadcast storm problem in other wireless networks such as MANETs or WSNs (see Section 3.4), the special characteristics of VANETs make it necessary to propose new schemes to cope with broadcast storm issues in these networks.

Regarding VANETs, previously proposed broadcast storm mitigation schemes

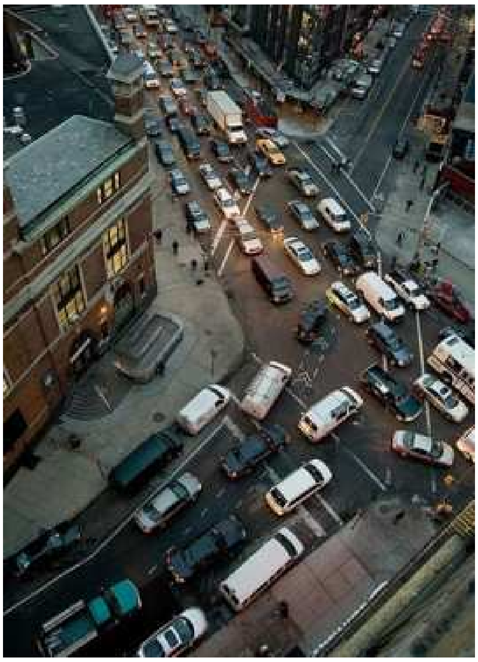


Figure 8.1: Example of a real scenario where a broadcast storm could be found.

have been only validated using simple scenarios such as a highway (several lanes, without junctions) [SP08, SPC09], or a Manhattan-style grid scenario [KEOO04].

In this chapter, we present a new scheme called *Street Broadcast Reduction* (SBR), which uses location and street information to facilitate the dissemination of warning messages so as to mitigate the broadcast storm problem found in 802.11p based VANETs. We also compare our approach with previous proposals, highlighting the benefits of using our proposed SBR scheme.

This chapter is organized as follows: Section 8.2 introduces our proposed SBR scheme. Section 8.3 contains a formal description of the SBR scheme. Section 8.4 shows the performance evaluation obtained when using the SBR scheme in Manhattan scenarios. In Section 8.5 we introduce how the Street Broadcast Reduction Scheme can be used in real maps. Simulation results are then discussed in Section 8.6. Finally, Section 8.7 concludes this chapter.

8.2 SBR: the Proposed Broadcast Storm Reduction Algorithm

In this section, we present the *Street Broadcast Reduction scheme* (SBR) - our novel proposal to reduce the broadcast storm problem in urban scenarios. In urban scenarios, and at the frequency of 5.9 GHz (i.e., the frequency band of the 802.11p standard), radio signals are highly directional and will experience a very

Algorithm 1 Street_Broadcast_Reduction_Send()

```
$P_w$ = AC3;    // set the highest priority
$P_b$ = AC1;    // set default priority
$ID$ = 0;       // initialize sequence number of messages
while (1) do
    if (vehicle$_i$ is in warning mode) then
        create message $m$;
        set $m$.priority = $P_w$;
        set $m$.seq_num = $ID$++;
        broadcast warning message ($m$);
        sleep ($T_w$)
    else
        create message $m$;
        set $m$.priority = $P_b$;
        broadcast beacon ($m$);
        sleep ($T_b$)
```

low depth of penetration. Hence, in most cases, buildings will absorb radio waves at this frequency, making communication only possible when the vehicles are in line-of-sight.

In our scheme, vehicles operate in two modes: (a) warning, and (b) normal. Warning mode vehicles inform other vehicles about their status by sending warning messages periodically (every T_w seconds). These messages have the highest priority at the MAC layer. We assume that the warning messages sent by warning mode vehicles can be received by all vehicles that are within the radio range, and so flooding offers the best reliability in terms of coverage. Normal mode vehicles enable the diffusion of these warning packets and, periodically (every T_b seconds), they also send *beacons* with information such as their positions, speed, etc. These periodic messages have lower priority than warning messages and are not propagated by other vehicles. With respect to warning messages, each vehicle is only allowed to propagate them once for each sequence number, i.e., older messages are dropped.

Algorithms 1 and 2 describe our SBR scheme. In the Street Broadcast Reduction mechanism, $vehicle_i$ indicates each vehicle in the scenario; m indicates each message sent or received by each vehicle; *warning* represents a warning message generated by a warning mode vehicle; *beacon* represents a normal message generated by a normal vehicle; T_w is the interval between two consecutive warning messages; T_b is the interval between two consecutive normal messages; P_w indicates the priority of the warning messages and P_b indicates the priority of the normal messages.

When a $vehicle_i$ starts the broadcast of a message, it sends m to all its neighbors. When another vehicle receives m for the first time, it rebroadcasts it by further relaying m to its neighbors. Depending on their characteristics, every vehicle repeats $send(warning)$ or $send(beacon)$ operations periodically with different periods (T_w and T_b, respectively).

Figure 8.2 shows the Send() algorithm state machine. When a new message

Algorithm 2 Street_Broadcast_Reduction_OnRecv()

```
for (every received message) do
    if ($m$ is is a warning and $m.seq\_num$ received for the first time) then
        if (distance between sender and receiver $> D$ or both vehicles are in different streets) then
            rebroadcast($m$)
        else
            discard($m$);
            /* warnings are only rebroadcasted when additional coverage area is high or they can be propagated to different streets */
    else
        discard($m$);
        // duplicated warnings and beacons are not rebroadcasted
```

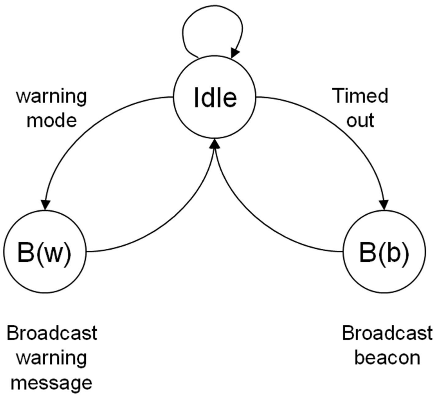


Figure 8.2: State machine corresponding to the Send() algorithm.

m is received, the vehicle tests whether m has already been received. To achieve this, each vehicle maintains a list of message IDs. An incoming warning message ID is inserted in the list if m is received for the first time (i.e. its ID has not been previously stored in the list), and if so it is rebroadcasted to the surrounding vehicles only when the distance d between sender and receiver is higher than a distance threshold D, or the receiver is in a different street than the sender.

We consider that two vehicles are in a different street when: (i) both are indeed in different roads (this information is obtained by on-board GPS systems with integrated street maps), or (ii) the receiver, in spite of being in the same street, is near an intersection. Hence, warnings can be rebroadcasted to vehicles which are traveling on other streets. If the message is a *beacon*, it is simply discarded since we are not interested in the dissemination of beacons. Figure 8.3 shows the OnRecv() algorithm flowchart.

Figure 8.4 shows an example where shaded rectangles represent buildings. When vehicle A broadcasts a warning message, it is only received by neighboring

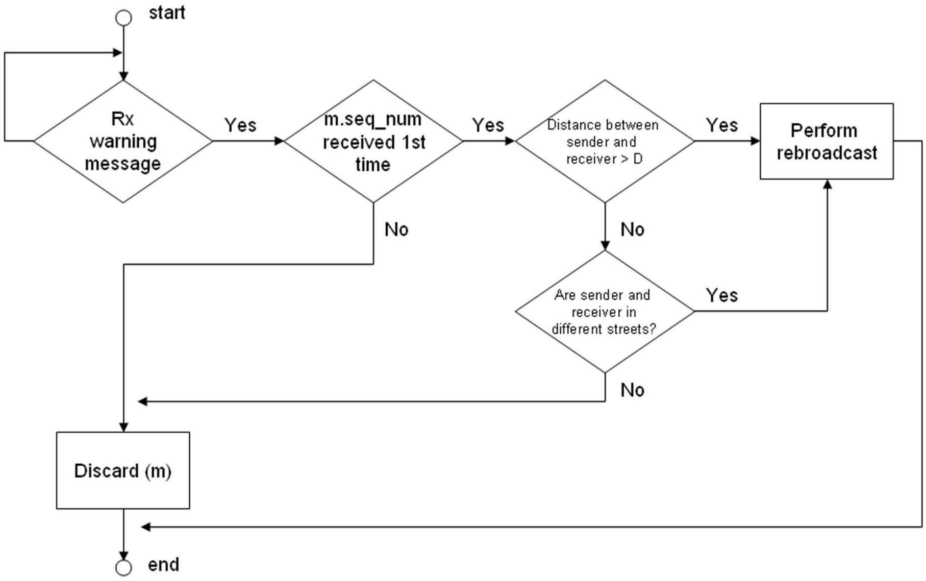


Figure 8.3: OnRecv() flowchart.

vehicles B, C, and D because buildings interfere with the radio signal propagation. In this situation, if we use distance or location-based schemes, vehicles B, C, and D will rebroadcast the message only if distances $d1$, $d2$ and $d3$, respectively, are large enough (i.e., the distance is larger than a distance threshold D), or its additional coverage areas are wide enough (i.e., the additional coverage is larger than a coverage threshold th_{AC}). So, supposing that only vehicle C meets this condition, the warning message could still not be propagated to the rest of vehicles (i.e., E, F, and G).

Our SBR scheme solves this problem. In SBR, vehicle D will rebroadcast the warning message since vehicle D is in a different street than vehicle A. In this way, the warning message will arrive to all the vehicles depicted in only four hops. In modern *Intelligent Transportation Systems* (ITS), vehicles are equipped with on-board GPS systems containing integrated street maps. Hence, location and street information can be readily used by SBR to facilitate dissemination of warning messages.

Note that distance and location schemes can be very restrictive, especially when buildings interfere with radio signal propagation. Without SBR, warning messages will not arrive at vehicles E, F and G due to the presence of buildings. Also, SBR can be combined with the location based scheme. When the additional coverage area is wide enough, vehicles will rebroadcast the received warning message. However, when the additional coverage area is very low, vehicles will rebroadcast warning messages only if they are in a different street. Next, we formally describe our proposed mechanism.

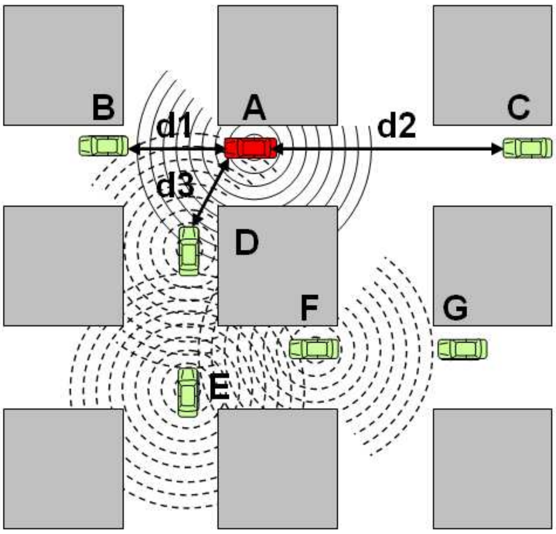


Figure 8.4: The Street Broadcast Reduction scheme: example scenario.

8.3 Formal Description of the SBR Algorithm

In this section we formally describe the previously presented SBR Algorithm using the Set Theory.

8.3.1 Definition of the Available Sets

Let us define three different sets (V, S, and J) as presented in Equations 8.1, 8.2, and 8.3:

$$V = \{v_i : 1 \leq i \leq n_v\} \tag{8.1}$$

$$S = \{s_i : 1 \leq i \leq n_s\} \tag{8.2}$$

$$J = \{j_i : 1 \leq i \leq n_j\} \tag{8.3}$$

where V represents the set of vehicles, S represents the set of streets, and J the represents the set of junctions between streets. n_v, n_s, and n_j represent the total number of vehicles, streets, and junctions in the scenario, respectively.

8.3.2 Definition of the Different Functions

There are different functions that allows us to operate with the above defined sets.

8.3.2.1 Functions to Operate with Vehicles

For modeling, each vehicle is defined as a point $v(x, y)$. There are two functions defined for vehicles:

- **position**, that returns the position (x, j) in cartesian coordinates of vehicle v_i at time t. When working with coordinates, we use the notation ".x" to state that we are using the X coordinate, and the notation ".y" to refer to the Y coordinate.
  $pos(v_i, t) \longrightarrow (f : V, \Re \rightarrow \Re^2)$
- **is_in_street**, that determines whether a point $p(x, y)$ is in a determined street, i.e. whether the point p is included within the rectangle involving the extremes of the street and a threshold (th_s) that represents the street's width.
  $is\_in\_street(s_i, p) \longrightarrow (f : S, \Re^2 \rightarrow \{true, false\})$

$$
\begin{aligned}
&is\_in\_street(s_i, p) = \\
&(min(start(s_i).x, end(s_i).x) - th_s \leq x \leq max(start(s_i).x, end(s_i).x) + th_s) \ \wedge \\
&\quad (min(start(s_i).y, end(s_i).y) - th_s \leq y \leq max(start(s_i).y, end(s_i).y) + th_s)
\end{aligned}
\tag{8.4}
$$

8.3.2.2 Functions to Operate with Streets

Each street is defined as a straight line linking two junctions: j_{start} and j_{end}. There are several functions defined for streets:

- **start**, that returns the start junction's position (x, y) of the street s_i.
  $start(s_i) \longrightarrow (f : S \rightarrow \Re^2)$
- **end**, that returns the end junction's position (x, y) of street s_i.
  $end(s_i) \longrightarrow (f : S \rightarrow \Re^2)$
- **line**, that returns the line formed by the two junctions that define street s_i. The line is in the form $Ax + By + C = 0$.
  $line(s_i) \longrightarrow (f : S \rightarrow \Re^3)$

  $$line(s_i) = \Delta y_s \cdot x - \Delta x_s \cdot y + (\Delta x_s \cdot start(s_i).y + \Delta y_s \cdot start(s_i).x) \tag{8.5}$$

  where $\Delta y_s = end(s_i).y - start(s_i).y$, and $\Delta x_s = end(s_i).x - start(s_i).x$
- **have_common_junct**, that determines whether two streets have a junction in common.
  $have\_common\_junct(s_i, s_j) \longrightarrow (f : S, S \rightarrow \{true, false\})$

$$
\begin{aligned}
have\_common\_junct(s_i, s_j) \ = \ & (start(s_i) = start(s_j)) \ \vee \ (start(s_i) = end(s_j)) \ \vee \\
& (end(s_i) = start(s_j)) \ \vee \ (end(s_i) = end(s_j))
\end{aligned}
\tag{8.6}
$$

- **ang_diff**, that computes the angular difference between two streets (i.e., the minimum angle between the vectors representing the streets). The two streets must have a vertex in common.

  $ang\_diff(s_i, s_j) \longrightarrow (f : S, S \rightarrow \Re)$

  $$ang\_diff(s_i, s_j) = min(\alpha(s_i, s_j), 360 - \alpha(s_i, s_j)) \tag{8.7}$$

  where

  $$\begin{aligned}\alpha(s_i, s_j) = {} & atan2(|end(s_i).y - start(s_i).y|, |end(s_i).x - start(s_i).x|) - \\ & atan2(|end(s_j).y - start(s_j).y|, |end(s_j).x - start(s_j).x|)\end{aligned} \tag{8.8}$$

Other functions used in the mathematical modeling of our solution are:

- **distance**, that returns the Euclidean distance between two points.

  $dist(p_0, p_1) \longrightarrow (f : \Re^2, \Re^2 \rightarrow \Re)$

  $$dist(p_0, p_1) = \sqrt{(p_0.x^2 - p_1.x^2) + (p_0.y^2 - p_1.y^2)} \tag{8.9}$$

- **min_distance**, that returns the minimum distance between a point p and a line l in the form $Ax + By + C = 0$, calculated as the distance between the point, and the point of the line which results in intersecting a perpendicular line which passes through p.

  $d_{min}(p, l) \longrightarrow (f : \Re^2, \Re^3 \rightarrow \Re)$

  $$d_{min}(p, l) = \frac{|Ax + By + C|}{\sqrt{A^2 + B^2}} \tag{8.10}$$

8.3.2.3 SBR Formal Definition

We call Ω_j, t the set of streets which are visible from the position of vehicle $j(v_j)$ on time t. The set of streets which are visible from the position of vehicle $j(v_j)$ on time t can be calculated as follows:

$$\Omega_{j,t} = \underbrace{\Phi_{j,t} \cup \Psi_{j,t}}_{streets\_located} \cup \underbrace{\Theta_{j,t} \cup \Upsilon_{j,t}}_{reachable\_streets} \tag{8.11}$$

We can decompose this set in a series of subsets:

- $\Phi_{j,t}$: set of streets in which v_j is located due to its position in the map.

$$\begin{aligned}\Phi_{j,t} = \{\varphi_i : \varphi_i \in S \ \wedge \ d_{min}(line(\varphi_i), pos(v_{j,t})) < th_s \\ \wedge\, is\_in\_street(\varphi_i, pos(v_{j,t}))\}\end{aligned} \tag{8.12}$$

- $\Psi_{j,t}$: set of streets in which v_j is located due to its proximity to a junction. A vehicle is near a junction when the distance between the junction and the vehicle is below a threshold (th_c).

$$\begin{aligned}\Psi_{j,t} = \{\psi_i : \psi_i \in S \ \wedge \ d_{min}(pos(v_{j,t}), start(\psi_i)) < th_c \ \vee \\ d_{min}(pos(v_{j,t}), end(\psi_i)) < th_c\}\end{aligned} \tag{8.13}$$

- $\Theta_{j,t}$: set of streets reachable (i.e., it has visibility) by v_j because they are adjacent to streets where the vehicle is located and the angular difference between these streets and the previous ones is below a threshold (th_a).

$$\begin{aligned}\Theta_{j,t} \ &= \ \{\theta_i : \theta_i \in S \ \wedge \ \theta_i \notin (\Phi_{j,t} \cup \Psi_{j,t}) \ \wedge \ \exists s_k | s_k \in (\Phi_{j,t} \cup \Psi_{j,t}) \ \wedge \\ &\quad have\_common\_junct(\theta_i, s_k) \wedge ang\_diff(\theta_i, s_k) < th_a\}\end{aligned} \tag{8.14}$$

- $\Upsilon_{j,t}$: set of streets reachable by v_j because there is a chain of streets (linked by a junction), and angular difference between any pair of streets in the chain is below a threshold (th_a).

$$\begin{aligned}\Upsilon_{j,t} \ &= \ \{v_i : v_i \in S \ \wedge \ v_i \notin (\Phi_{j,t} \cup \Psi_{j,t} \cup \Theta_{j,t}) \ \wedge \\ &\quad \exists S' | S' \subseteq S \wedge \ v_i \in S' \wedge (\exists s'_k | s'_k \in S' \wedge s'_k \in (\Phi_{j,t} \cup \Psi_{j,t} \cup \Theta_{j,t})) \ \wedge \\ &\quad (\forall s'_i | s'_i \in S' \Rightarrow (\exists! s'_j | s'_j \in S' \wedge (start(s'_i) = start(s'_j)) \ \vee \ (start(s'_i) = end(s'_j)))) \wedge \\ &\quad (\forall s'_i | s'_i \in S' \Rightarrow (\exists! s'_j | s'_j \in S' \wedge (end(s'_i) = start(s'_j)) \ \vee \ (end(s'_i) = end(s'_j)))) \wedge \\ &\quad (\forall s'_i, s'_j | s'_i \in S' \wedge s'_j \in S' \Rightarrow ang\_diff(s'_i, s'_j) < th_a))\}\end{aligned} \tag{8.15}$$

Given two vehicles, v_s and v_r, in a situation where v_s is the sender and v_r is the receiver, and supposing that the radio signal is strong enough to reach v_r, the SBR scheme will be enabled only if the following condition is satisfied:

$$\begin{gathered}(\exists \omega_s, \omega_r | \omega_s \in \Phi_{s,t} \wedge \omega_r \in \Psi_{r,t} \wedge \omega_r \notin \Omega_{s,t} \wedge (ang\_diff(\omega_s, \omega_r) > th_a) \ \wedge \\ (\exists j | j \in J \wedge (start(\omega_r) = j \vee end(\omega_r) = j) \wedge dist(pos(v_r, t), j) < th_c \\ (\forall v_i | v_i \in V \wedge v_i \neq v_r \Rightarrow dist(pos(v_i, t), j) \geq dist(pos(v_r, t), j))))\end{gathered} \tag{8.16}$$

which means that the SBR scheme is activated (i.e., it allows that receiver to rebroadcast) when the two vehicles are in different streets, or the receiver node is near a junction and it is the nearest node to the center of the junction.

Table 8.1: Parameter values for the different Manhattan-based scenarios

Parameter	**Value**
maximum speed	50 km/h
map area size	$2500m \times 2500m$
distance between streets	$100m$
number of warning mode vehicles	3
downtown size	$1000m \times 1000m$
downtown speed (min.-max.)	$5 - 30$ km/h
downtown probability	0.6
warning packet size	$256bytes$
normal packet size	$512bytes$
packets sent by vehicles	1 *per second*
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
Radio Propagation Model	BDAM [MTC$^+$09b]
maximum transmission range	$250m$
SBR distance threshold (D)	$200m$

8.4 SBR Simulation Results in Manhattan-based Scenarios

In this section, we perform a detailed analysis to evaluate the impact of the proposed SBR scheme on the overall system performance when using Manhattan-based scenarios. We compare the impact of our scheme with respect to a flooding scheme without limitation of broadcasts, and a location-based broadcast scheme.

Since performance results are highly related to the specific scenarios used, and due to the random nature of the mobility model, we performed several simulations to obtain reasonable confidence intervals. All the results shown here have a 90% confidence interval.

We evaluated the following performance metrics: (a) percentage of blind vehicles, (b) warning notification time, and (c) number of packets received per vehicle. The percentage of blind vehicles is the percentage of vehicles that do not receive the warning messages sent by accident vehicles. These vehicles remain blind because of their positions, due to packet collisions, or due to signal propagation limitations. The warning notification time is the time required by normal vehicles to receive a warning message sent by a "warning mode" vehicle (a vehicle that broadcasts warning messages). Table 8.1 shows the simulation parameters used.

Tseng et al. [TNCS02] demonstrated that the location-based scheme is preferred, since it reduces redundancy without compromising the number of vehicles receiving the messages. So, we evaluate the performance of our proposed scheme (SBR) with respect to: (i) a flooding scheme without limitation of rebroadcasts, (ii) a location-based scheme, and (iii) a combination of our SBR with the location-based scheme.

Figure 8.5 shows the warning notification time obtained when simulating 150 vehicles. As shown, when the effect of obstacles is not taken into account (see Figure 8.5a), all the schemes behave in a similar way, although the SBR scheme needs less time to inform 60% of the vehicles (only 0.18 seconds); the warning message propagation process ends in about 0.9 seconds for all schemes.

When accounting for obstacles (see Figure 8.5b), the SBR scheme, combined with the location-based scheme, outperforms other solutions since the warning notification time is lower (information reaches 50% of the vehicles in only 0.78 seconds), and the percentage of blind vehicles is lower than others. The presence of buildings in signal propagation paths results in the need for more time to complete the propagation process (1.2 seconds).

The percentage of blind vehicles will largely depend on the presence of buildings (see Figure 8.6a). When obstacles are not taken into account, the percentage of blind vehicles is very similar for all the schemes. When taken into account, the percentage of blind vehicles increases significantly. Our proposed SBR scheme, when combined with the location-based technique, behaves better than others (46% of blind vehicles). As for the total number of packets received per vehicle (see Figure 8.6b), we demonstrate that, despite the high number of packets received with the flooding scheme, it behaves worse in terms of warning message notification time and the percentage of blind vehicles due to the broadcast storm. When accounting for obstacles, our proposal yields the best performance and it outperforms both the flooding scheme and the location-based scheme. With respect to the flooding scheme, SBR reduces up to 95.84% the number of packets received. As far as the location scheme is concerned, SBR increases the percentage of vehicles receiving the warning messages by around 8%.

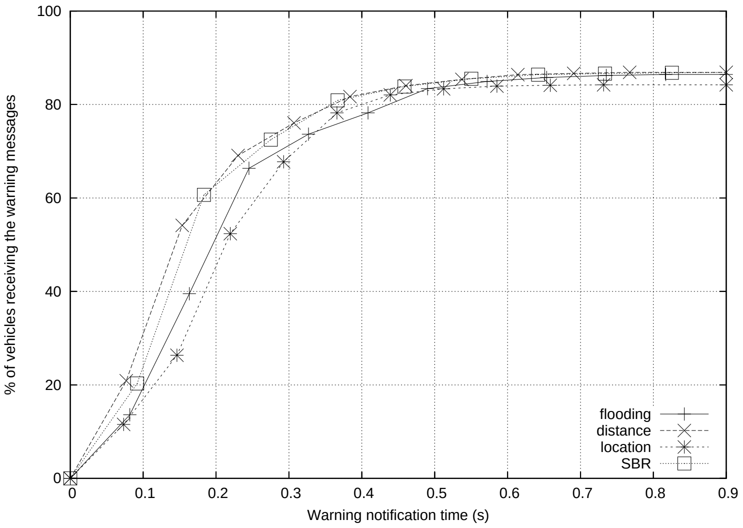
8.5 The Street Broadcast Reduction (SBR) Scheme in Real Map Scenarios

In this section, we study the performance of our proposal in real map scenarios.

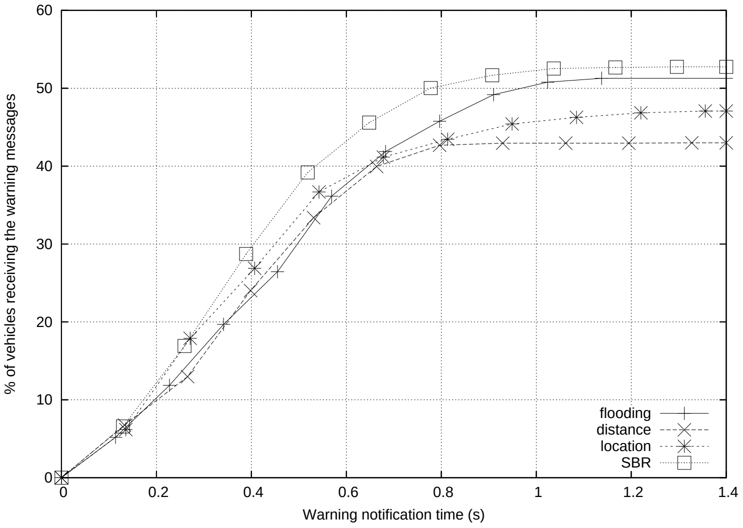
Figure 8.7 shows an example in a real map scenario where shaded polygons represent buildings. When vehicle A broadcasts a warning message, it is only received by neighboring vehicles B, C, and D because buildings interfere with the radio signal propagation. In this situation, if we use distance or location-based schemes, vehicles B, C, and D will rebroadcast the message only if distances $d1$, $d2$ and $d3$, respectively, are large enough (i.e., the distance is larger than a distance threshold D), or its additional coverage areas are wide enough (i.e., the additional coverage is larger than a coverage threshold th_{AC}). So, supposing that only vehicle C meets this condition, the warning message could still not be propagated to the rest of vehicles (i.e., E, F, and G).

In SBR, vehicle D will rebroadcast the warning message since vehicle D is in a different street than vehicle A. Unlike other proposed broadcast reduction techniques, SBR allows that the warning message will arrive to all the vehicles in the scenario in only four hops.

Simulation results presented in this section were obtained simulating real city maps with buildings. The simulated topologies represent the downtown area of Valencia City (Spain), and Manhattan City (KS, USA). They were obtained from

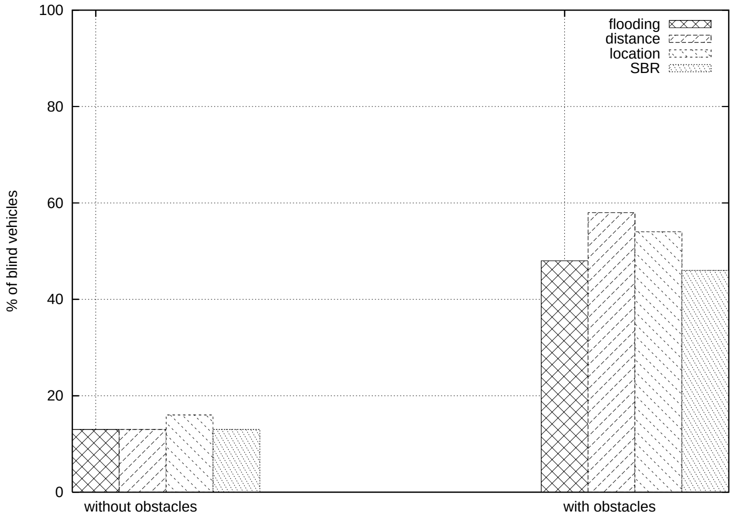


(a)

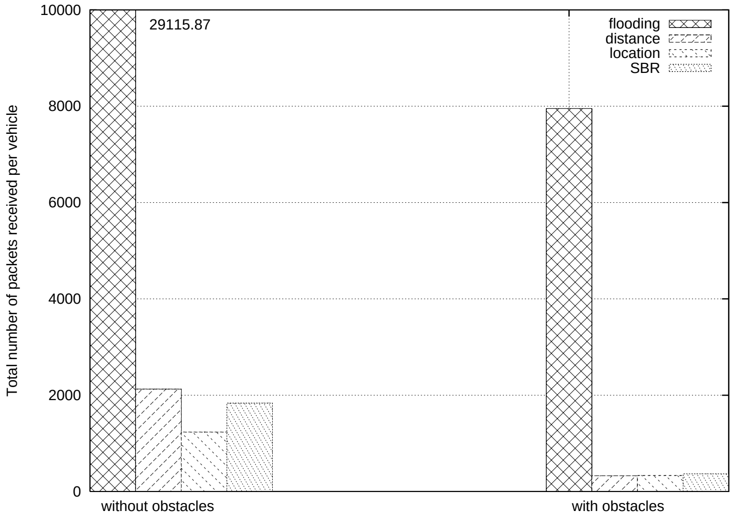


(b)

Figure 8.5: Average propagation delay when varying the dissemination scheme: (a) without obstacles, and (b) with obstacles.



(a)



(b)

Figure 8.6: (a) Percentage of blind vehicles vs. dissemination scheme, and (b) total number of packets received per vehicle vs. dissemination scheme, both accounting for no obstacles and the presence of obstacles.

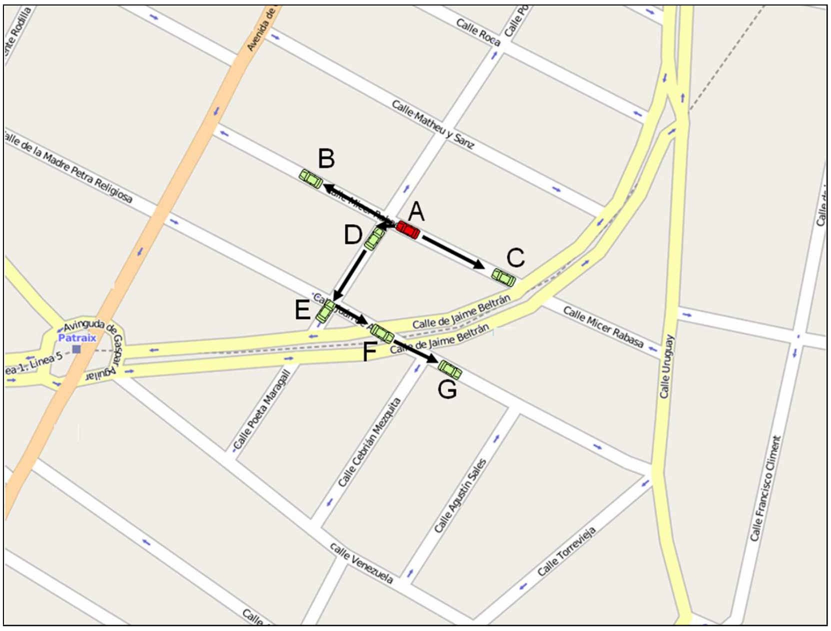


Figure 8.7: The Street Broadcast Reduction scheme in real maps: example scenario taken from the city of Valencia in Spain.

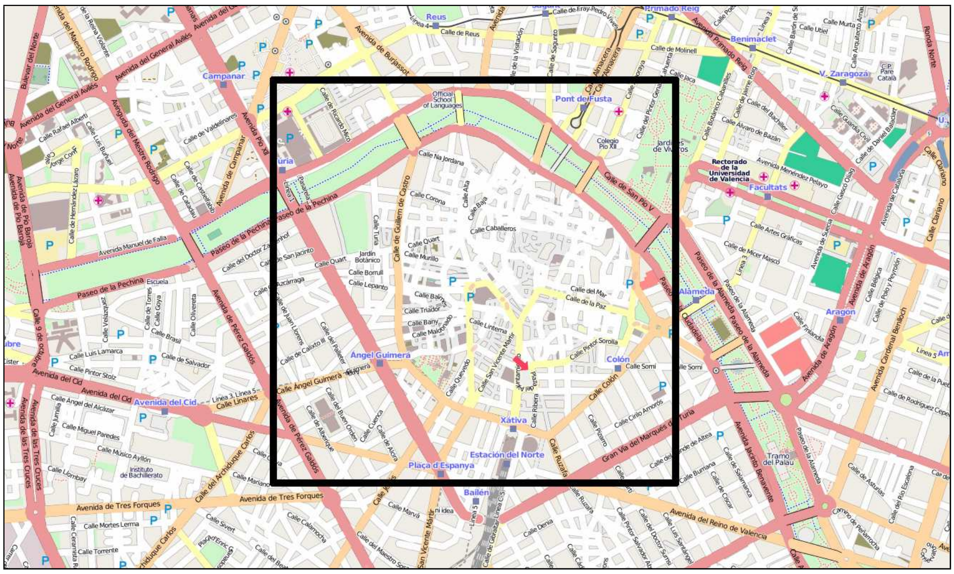
OpenStreetMap. Figure 8.8 shows the layout of Valencia City used in our simulations.

8.6 Simulation Results Obtained for the SBR in Real Maps

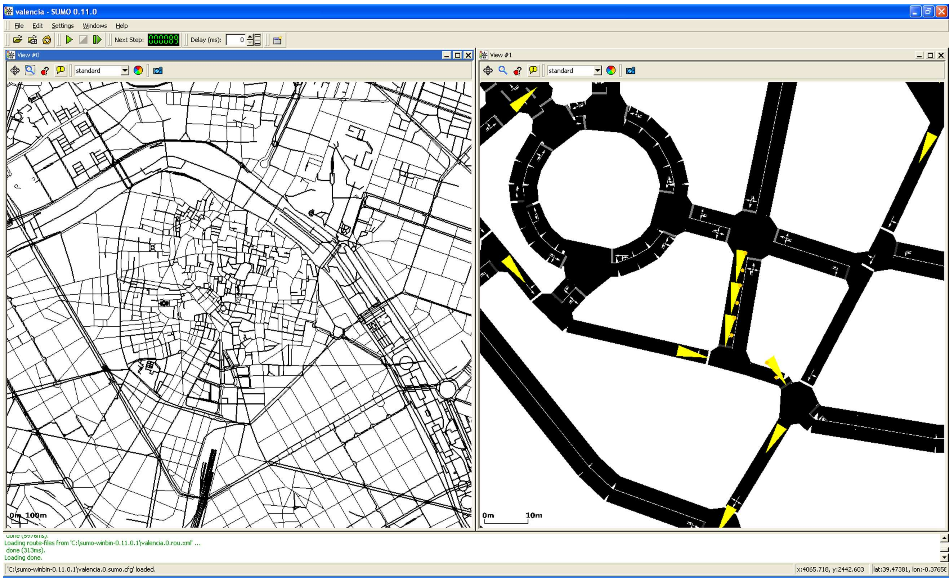
In this section, we perform a detailed analysis to evaluate the impact of the proposed SBR scheme on the overall system performance. In order to study the effect of using real maps, we compare the impact of our scheme in two different scenarios: the city of Manhattan, and the city of Valencia. Table 8.2 shows the simulation parameters used.

We evaluated the performance of our SBR proposed scheme with respect to: (i) a distance-based scheme, and (ii) a location-based scheme, using two different scenarios: (i) a real map of Manhattan, and (ii) a real map of Valencia, with an average density of 75 vehicles/km^2.

Figure 8.9 shows the warning notification times obtained. When the simulation scenario is the city of Manhattan (see Figure 8.9a), the system needs only one second to inform at least 75% of the vehicles for all the schemes, and the message dissemination process ends in less than 2 seconds. The percentage of vehicles receiving the warning message is an 8% higher when using SBR compared to both the distance-based and the location-based schemes. Concerning the Manhattan



(a)



```
Loading route-files from 'C:\sumo-winbin-0.11.0.1\valencia.0.rou.xml' ...
 done (313ms).
Loading done.
'C:\sumo-winbin-0.11.0.1\valencia.0.sumo.cfg' loaded.
x:4065.718, y:2442.603   lat:39.47381, lon:-0.37658
```

(b)

Figure 8.8: Simulated scenario of Valencia City: (a) OpenStreetMap layout, and (b) the SUMO converted version. The box shows our simulated area.

Table 8.2: Parameter values for the real map simulations

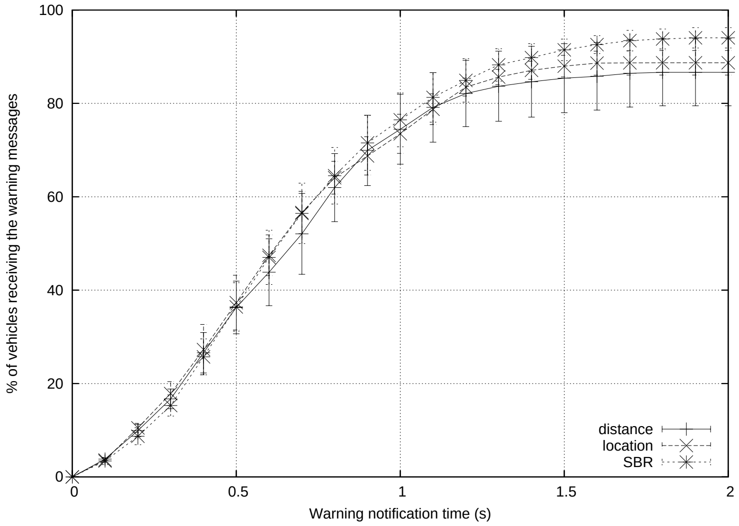
Parameter	**Value**
number of vehicles	300
map area size	$2000m \times 2000m$
maximum speed	50 km/h
number of warning mode vehicles	3
warning packet size	$256bytes$
normal packet size	$512bytes$
packets sent by vehicles	1 *per second*
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
Radio Propagation Model	RAV
maximum transmission range	$400m$
SBR distance threshold (D)	$300m$

scenario, warning messages reach longer distances because of the lack of direction changes in the straight streets that characterize this map.

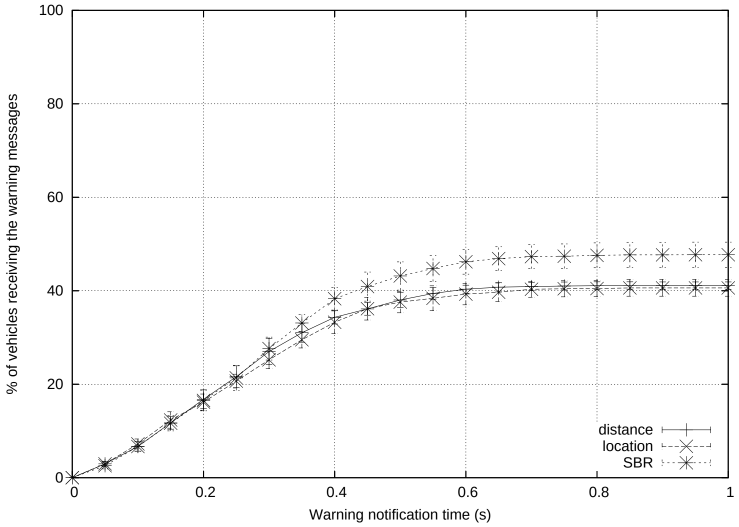
When simulating the city of Valencia (see Figure 8.9b), some noticeable differences appear. First of all, the percentage of vehicles receiving warning messages decreases from about the 90-95% in a Manhattan scenario to less than 50%, since the complexity of the layout and the arrangement of the buildings significantly interfere with the signal propagation process. Thus, the highly directional radio signal reduces drastically the probability of reaching longer distances. As for the warning notification time, we obtained better results using the SBR scheme. The warning messages reach 40% of the vehicles in 0.45 seconds. Also notice that the message dissemination process ends before 1 second for all schemes. This time is 50% lower than the obtained in the map of Manhattan City because the information is only spread to nearby vehicles due to the complexity of the layout.

As for the percentage of blind nodes, Figure 8.10a shows how it will largely depend on the chosen simulation scenario. There are few blind vehicles when simulating the map of Manhattan for all schemes (less than 15%), and the percentage of blind nodes is reduced by half when using SBR. Nevertheless, less than 50% of the vehicles are aware of warning messages when simulating the map of Valencia. If we use this more complex scenario we find that, when the SBR scheme is adopted, the percentage of vehicles which receive warning messages increases by 8% when compared to the distance and location-based techniques.

Finally, Figure 8.10b shows the total number of packets received per vehicle, which is a measure of the degree of contention in the channel. In the map of Manhattan the signal propagates easily due to the streets' position, and so the vehicles receive many duplicated messages. However, in the map of Valencia, the more complex layout makes difficult signal propagation, and so the number of messages received decreases. These messages are received only by vehicles which are likely to face the dangerous situation, i.e. they are in the same street or in nearby ones. When simulating the map of Valencia, the number of packets received

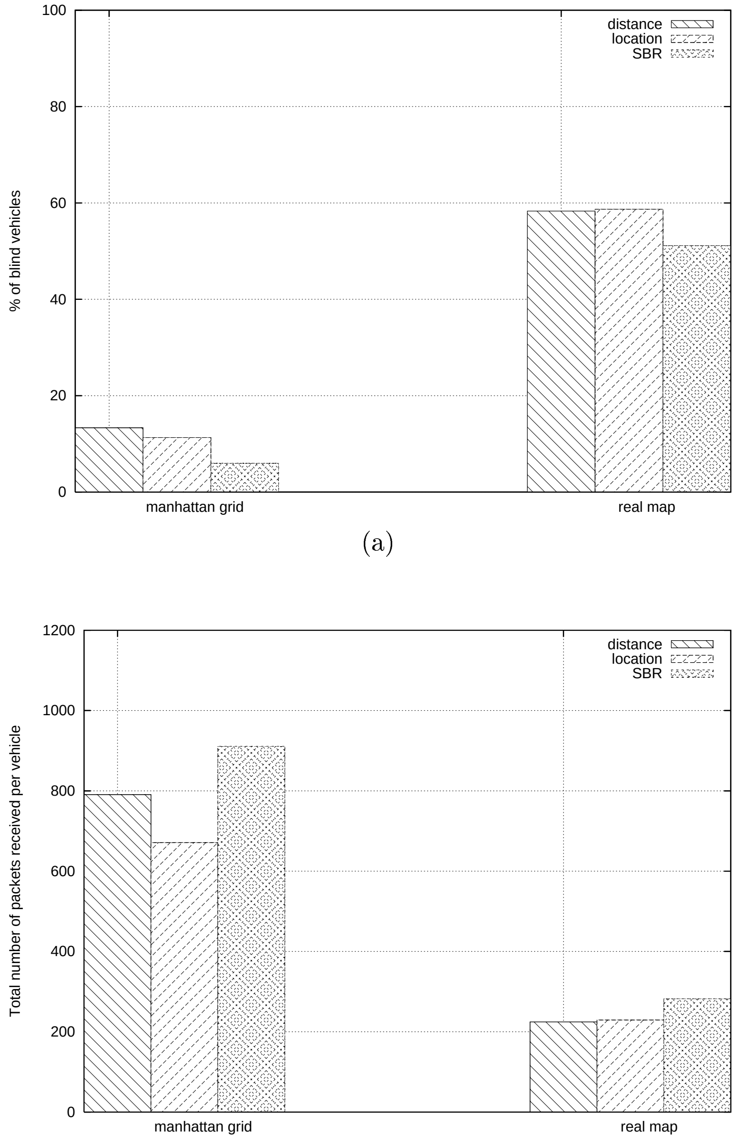


(a)



(b)

Figure 8.9: Average propagation delay when varying the simulation scenario, using both the map of: (a) Manhattan, and (b) Valencia.



(a)

(b)

Figure 8.10: (a) Percentage of blind vehicles vs. scenario layout, and (b) total number of packets received per vehicle vs. scenario layout, accounting for both Manhattan and Valencia scenarios.

per vehicle is almost the same for the distance and location-based schemes; when using SBR the number of packets received increases slightly, but the percentage of vehicles which receive warning messages increases to a greater extent.

Authors in [TNCS02] demonstrated that the location-based scheme was more efficient than the distance-based scheme, since it reduces redundancy without compromising the number of vehicles receiving the warning message. Nevertheless, the main drawback for using this scheme is the high computational cost of calculating the additional coverage. Our simulation results demonstrate that SBR outperforms these schemes without introducing much complexity and calculations.

8.7 Summary

Achieving efficient dissemination of messages is of utmost importance in vehicular networks to warn drivers of critical road conditions. However, broadcasting of warning messages in VANETs can result in increased channel contention and packet collisions due to simultaneous message transmissions.

In this chapter we introduced the *Street Broadcast Reduction* (SBR) scheme to mitigate broadcast storms in urban scenarios. SBR improves the performance of warning message dissemination. Simulation results show that SBR outperforms other schemes in high density urban scenarios, yielding a lower percentage of blind vehicles while drastically alleviating the broadcast storm problem, being thus suitable for real scenarios. Our experiments also highlight that the message propagation behavior in realistic scenarios based on maps of actual cities differs greatly from more traditional Manhattan-style scenarios. Thus, we consider that the results obtained using unrealistic scenarios should be revised, and we recommend the adoption of real maps whenever possible.

Chapter 9

Conclusions, Publications and Future Work

Throughout this thesis several contributions have been made to the area of Vehicular Ad Hoc Networks and Intelligent Transportation Systems. Our purpose was to design a system for reducing the Emergency Services Responsiveness, in order to improve the chances of survival for passengers involved in car accidents. Hence, we proposed a novel warning dissemination protocol which improves traffic safety by increasing the warning message broadcast effectiveness in vehicular networks. This was achieved by reducing the broadcast storm problem while maintaining a high message dissemination effectiveness towards surrounding vehicles.

Since simulation was required to assess our proposals, the optimum tuning of a commonly used network simulator such as ns-2 was required to be used in VANETs. We designed a simulation framework that was able to enhance currently available simulation results regarding vehicular networks in a very significant manner. We have shown, based on experimental results, that the different goals have been achieved.

We now proceed to summarize the most relevant contributions of this work:

- Proposal of a system for reducing the Emergency Services Responsiveness in order to improve the chances of survival for passengers involved in car accidents. It includes the Street Broadcast Reduction (SBR) scheme, a novel protocol to improve the broadcast of warning messages, with the aim of increasing traffic safety, and specially designed to be used on vehicular networks. Moreover, SBR mitigates the broadcast storm problem.

- Evaluation of the SBR scheme using realistic VANET scenarios, unlike other previous works that were mostly evaluated under simplistic simulation environments.

- Development of CityMob, an application to generate realistic mobility pattern traces to simulate VANET on urban scenarios.

- Determination of the key factors affecting *Warning Message Dissemination*

(WMD) in VANETs in order to reduce the amount of required simulation time when evaluating VANETs.

- Enhancing the ns-2 simulator in order to allow simulating real maps obtained from openstreetmap.org, making it possible for researchers to get more realistic results in their simulations.

- Proposal of four realistic Radio Propagation Models (RPMs): (i) The *Distance Attenuation Model* (DAM), which considers the signal attenuation due to the distance between the vehicles, (ii) the *Building Model* (BM), which considers that communication among vehicles is only possible when they are in line-of-sight, (iii) the *Building and Distance Attenuation Model* (BDAM), which combines both DAM and BM models, and (iv) the Real Attenuation and Visibility Model (RAV), which uses both a realistic attenuation scheme (using real experimental data), and a realistic visibility scheme (accounting for the effect of buildings in radio signal propagation and their presence in real map layouts).

Having accomplished all of our predefined goals, we consider that the ultimate purpose of this thesis has been achieved successfully, and so we conclude this dissertation.

9.1 Publications Related to the Thesis

The research work related to this thesis has resulted in 13 publications; among them we have 3 journal articles (two of them indexed by the Journal Citation Reports (JCR) database), and 10 conference papers (4 of them indexed by the Computer Science Conference Ranking or the Computing Research and Education (CORE) lists). We now proceed by presenting a brief description of each of them.

9.1.1 Journals

[MTC$^+$09a] F. J. Martinez, C.-K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A Survey & Comparative Study of Simulators for Vehicular Ad Hoc Networks (VANETs)", in *Wireless Communications and Mobile Computing Journal*, Wiley, October 2009. DOI: 10.1002/wcm.859

This paper presents a comprehensive study and comparison of the various publicly available VANET simulation software and their components. In particular, we contrast their software characteristics, graphical user interface (GUI), popularity, ease of use, input requirements, output visualization capability, accuracy of simulation, etc. Finally, while each of the studied simulators provides a good simulation environment for VANETs, refinements and further contributions are needed before they can be widely used by the research community.

The mobility generators studied include SUMO, MOVE, CityMob, FreeSim, STRAW, Netstream, and VanetMobiSim. SUMO, MOVE, STRAW, and VanetMobiSim all have good software features and traffic model support. However, only VanetMobiSim provides excellent trace support. CityMob is good in software features and traffic model support. FreeSim exhibits good software characteristics but is limited in other features.

Among the network simulators studied, ns-2, GloMoSim, JiST/SWANS, and SNS all exhibit good software support. However, both ns-2 and GloMoSim are poor in scalability while JiST/SWANS is harder to use than others. In fact, none of the network simulators specifically addresses VANET scenarios and requirements, such as the consideration of 802.11p, obstacles, vehicular traffic flow, etc.

Finally, in terms of VANET simulators, we studied TraNS, GrooveNet, NCTUns, and MobiREAL. TraNS and MobiREAL both involve the coupling of a VANET mobility generator with a network simulator. GrooveNet and NCTUns, however, are self-contained simulators being GrooveNet capable of supporting hybrid simulations, i.e., communications between simulated vehicles and real vehicles. A survey of recently published papers shows that GrooveNet and NCTUns are more frequently used for VANET simulations than others. Although these four VANET simulators are now publicly available, we realize that further refinements, extensions, and contributions are needed before they can be widely accepted and used for supporting VANET research.

[MTC$^+$10b] F. J. Martinez, C.-K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A Street Broadcast Reduction Scheme (SBR) to Mitigate the Broadcast Storm Problem in VANETs", in *Wireless Personal Communications Journal*, Springer, April 2010. DOI: 10.1007/s11277-010-9989-4

In this paper, we present Street Broadcast Reduction (SBR), a novel scheme that mitigates the broadcast storm problem in VANETs. SBR also reduces the warning message notification time and increases the number of vehicles that are informed about the alert.

Achieving efficient dissemination of messages is important in vehicular networks so as to warn drivers of critical road conditions. However, broadcasting of warning messages in VANETs can result in increased channel contention, and packet collisions due to simultaneous message transmissions (usually known as the broadcast storm problem).

In this work, we introduce the Street Broadcast Reduction (SBR) scheme to reduce broadcast storm in urban scenarios and to improve the performance of warning message dissemination. SBR can be combined with the existing location-based scheme for further broadcast storm reduction. Simulation results show that when SBR is combined with the location-based scheme, it outperforms other schemes in high density urban scenarios, yielding a lower percentage of blind vehicles while drastically alleviating the broadcast storm problem.

[MTC+10a] F. J. Martinez, C.-K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Emergency Services in Future Intelligent Transportation Systems based on Vehicular Communication Networks", in *IEEE Intelligent Transportation Systems Mag.*, November 2010. DOI: 10.1109/MITS.2010.938166

In the past, people were focused on how to build efficient highways and roads. Over time, focus was made on mechanical and automotive engineering, in the pursuit of building faster cars to surmount greater distances. Later on, electronics technology impacted the construction of cars, embedding them with sensors and advanced electronics, making cars more intelligent, sensitive and safe to drive on. Now, innovations made so far in wireless mobile communications and networking technologies are starting to impact cars, roads, and highways. This impact will drastically change the way we view transportation systems of the next generation and the way we drive in the future. It will create major economic, social, and global impact through the transformation over the next period of 10-15 years.

Several research projects led by research institutes and car manufacturers around the world have positively impacted the future of IVC systems. Technologies have clearly contributed to the change in the course of actions to follow after an accident occurs; moving from a simple cellular phone call made by a witness, to the current eCall accident notification system provided in EU. In the near future, accident notification systems will be specially designed for post-collision rescue services. Combining V2V and V2I communications, new Intelligent Transportation Systems will emerge with the capability of improving the responsiveness of roadside emergency services.

This paper presents an overview of the current state-of-the-art, discusses current projects, their goals, and finally highlights how emergency services and road safety will evolve with the blending of vehicular communication networks with road transportation.

9.1.2 Indexed Conferences

[MTC+09b] F. J. Martinez, C.-K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Realistic Radio Propagation Models (RPMs) for VANET Simulations", in *IEEE Wireless Communications and Networking Conference (WCNC)*, Budapest, Hungary, April 2009.

In this paper we present three different RPMs that increase the level of realism of the physical layer model, thereby allowing us to obtain more accurate and meaningful results. These models are: (a) the Distance Attenuation Model (DAM), (b) the Building Model (BM), and (c) the Building and Distance Attenuation Model (BDAM). We evaluated these different models and compared them with the Two-ray Ground model implemented in ns-2.

We then carried out further study to evaluate the impact of varying some important parameters, such as vehicle density and building size, on VANET warning message dissemination. Simulation results confirmed that our proposed BDAM significantly affects the percentage of blind vehicles present and the number of received warning messages, and that our models can better reflect realistic scenarios.

[MCCM09a] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A Performance Evaluation of Warning Message Dissemination in 802.11p based VANETs", in *IEEE Local Computer Networks Conference (LCN)*, Zürich, Switzerland, October 2009.

In this paper we present a performance evaluation study analyzing the behavior of a generic Warning Message Dissemination mechanism (WMD) in an 802.11p based VANET.

We based our evaluation on the 2k factorial methodology to determine the most representative factors that affect the WMD mechanism performance. We carried out simulations to evaluate the impact of varying the characterizing factors on performance. Performance metrics evaluated are: (1) time required to propagate the warning messages, (2) the number of blind nodes (i.e., nodes that do not receive these packets) and (3) the number of packets received per node.

Simulation results show that the propagation delay is lower when node density increases, and that the percentage of blind nodes highly depends on this factor, too. Factors that affect the number of packets received the most are the downtown size, the probability of being in downtown and the number of nodes. The size of the packets sent does not affect the warning dissemination protocol's behavior.

[MFC$^+$10b] F. J. Martinez, M. Fogue, M. Coll, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Evaluating the Impact of a Novel Warning Message Dissemination Scheme for VANETs Using Real City Maps", in *IFIP Networking*, Chennai, India, May 2010.

In this paper we present the enhanced Street Broadcast Reduction (eSBR), a novel scheme for VANETs designed to mitigate the broadcast storm problem in real urban scenarios. We evaluate the impact that our scheme has on performance when applied to VANET scenarios based on real city maps.

Simulation results show that eSBR outperforms other schemes in high density urban scenarios, yielding a lower percentage of blind vehicles while drastically alleviating the broadcast storm problem, being thus suitable for real scenarios. Our experiments also highlight that the message propagation behavior in realistic scenarios based on maps of actual cities differs greatly from more traditional Manhattan-style scenarios. Thus, we consider that the results obtained using unrealistic scenarios should be revised, and we recommend the adoption of real maps whenever possible.

[MFC$^+$10a] F. J. Martinez, M. Fogue, M. Coll, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Assessing the Impact of a Realistic Radio Propagation Model on VANET Scenarios using Real Maps", in *IEEE International Symposium* *on Network Computing and Applications (IEEE NCA'10)*, Cambridge, MA USA, July 2010.

In this paper we present a new Radio Propagation Model (RPM), called Real Attenuation and Visibility (RAV), proposed to simulate more realistically both attenuation of wireless signals (signal power loss) and the radio visibility scheme (presence of obstacles interfering with the signal path). We evaluated this model and compared it against existing RPMs using real scenarios. We then carried out further studies to evaluate the impact of combining different attenuation and visibility schemes. Simulation results confirmed that our proposed RAV scheme can better reflect realistic scenarios, and significantly affects the percentage of blind vehicles, the channel contention, and the warning notification time.

9.1.3 International Conferences

[MCCM08b] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. "Citymob: a mobility model pattern generator for VANETs", in *IEEE Vehicular Networks and Applications Workshop (Vehi-Mobi, held with ICC)*, Beijing, China, May 2008.

In this paper we present CityMob, a mobility pattern generator for VANETs. Citymob allows researchers to easily create urban mobility scenarios, including the possibility to model car accidents. We designed and developed it targeting compatibility with the ns-2 simulator, and we implemented three different mobility models: Simple Model (SM), Manhattan Model (MM) and Downtown Model (DM).

Based on a flooding alert dissemintation protocol we show that the most realistic mobility model to simulate traffic accidents is the Downtown model. We also find that, for flooding to be effective, a moderate number of vehicles is required.

[MCC$^+$09] F. J. Martinez, J.-C. Cano, C. T. Calafate, P. Manzoni, and J.M. Barrios "Assessing the feasibility of a VANET", in *ACM Workshop on Performance Monitoring, Measurement and Evaluation of Heterogeneous Wireless and Wired Networks (PM2HW2N 2009, held with MSWiM)*, Tenerife, Spain, October 2009.

In this work we evaluate the feasibility of a VANET Warning System in which damaged vehicles send vehicle safety messages with high reliability and low delay. We performed a sensitivity study to evaluate the impact of varying some parameters in the proposed system. We varied the number of damaged vehicles, the total number of vehicles, as well as the priority and periodicity of the messages sent to study the impact on the time required to propagate the warning messages, the number of blind vehicles (i.e., vehicles that do not receive these packets) and the number of packets received per vehicle, in order to study the viability of our system.

We show that the warning notification time is lower when vehicle density increases, and that the percentage of blind vehicles highly depends on this factor. Finally, the results demonstrated that, to obtain the lowest possible warning notification time in our system, the best solution is that messages have different priorities depending on their characteristics.

[MCC$^+$10] F. J. Martinez, J.-C. Cano, C. T. Calafate, P. Manzoni, and J. M. Barrios "e-NOTIFY: A Proposal to Improve the Responsiveness of Emergency Services", in *Eighth European Dependable Computing Conference (ED CC)*, Valencia, Spain, April 2010.

In this paper we introduce e-NOTIFY, a novel proposal designed to improve the responsiveness of emergency services by reducing the time required to rescue the passengers involved in a car accident, and automatically managing and optimizing the medical and rescue resources needed.

9.1.4 National Conferences

[MCCM08a] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. "A VANET Solution to Prevent Car Accidents", in *XIX Jornadas de Paralelismo*, Castellón, Spain, September 2008.

In this work we present a driver warning system in which damaged vehicles send warning messages and the rest of the vehicles make the diffusion of these messages. We concentrated on diffusion of warning messages sent by damaged nodes in order to inform the rest of vehicles in the scenario in 802.11p-based VANETs. The target is to send vehicle safety messages with high reliability and low delay.

We performed a sensibility study to evaluate the impact of varying some parameters in the proposed advertisement system. We show that the propagation delay is lower when node density increases, and that the percentage of blind nodes (i.e., nodes that do not receive these packets) highly depends on this factor.

Finally, the results demonstrated that, to obtain the lowest possible propagation delay in our system, the best solution is that messages have different priorities depending on their characteristics.

[MCCM09b] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. "Evaluating Warning Dissemination in VANETs", in *XX Jornadas de Paralelismo*, La Coruña, Spain, September 2009.

In this paper we present a generic Warning Message Dissemination mechanism (WMD) in an 802.11p based VANET. In a WMD, warning mode vehicles notify nearby vehicles in order to improve traffic safety and to control traffic congestion. We carried out simulations to evaluate the impact of varying the characterizing factors on performance.

[FGM$^+$10] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Reducing the Emergency Services Response Time using Vehicular Networks", in *XXI Jornadas de Paralelismo*, Valencia, Spain, September 2010.

This work presents e-NOTIFY, a proposal which improves the responsiveness of emergency services. e-NOTIFY does not concentrate on reducing the number of accidents, but rather focuses on improving the rescue procedures. To this end, once the accident has occurred, e-NOTIFY tries to automatically and efficiently manage the emergency resources. Therefore, the main goal is to send SOS messages with precise information, high reliability and low delay, making it possible to predict the injury severity of occupants, and thus adapt the required rescue resources and reduce the response time of the emergency services.

9.2 Future work

In the development of this thesis several issues emerged which deserve further scrutiny in a future. The ones we consider most relevant are the following:

- To develop an adaptive Warning Message Dissemination mechanism, where vehicles will be able to modify the rebroadcast scheme (e.g. varying the data rate of warning and beacons, or varying the broadcast reduction technique used) in order to choose the best option according to the network conditions.
- To implement a real testbed using the SBR scheme. A real implementation would be required to assess its feasibility, and measuring its actual performance.
- To study different possibilities to improve the SBR scheme, for example to modify SBR to make it possible that a vehicle could decide when and how to rebroadcast the warning messages.
- To develop a Dynamic Mobility Model generator. Such application would generate more realistic traffic mobility patterns, making it possible that vehicle's movements could change "on-the-fly" when a warning message is received.
- To explore the advantages of developing hybrid vehicular communication systems which indeed combine V2V and V2I communications.
- To improve the warning message dissemination systems using smart characterization of the cities, where vehicles could adapt their traffic safety applications based on which city they are, and the roadmap of the particular city.

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