TESIS DE LA UNIVERSIDAD DE ZARAGOZA

2014

47

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# Adaptive Mechanisms to Improve Message Dissemination in Vehicular Networks

Departamento

Informática e Ingeniería de Sistemas

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ISSN 2254-7606

Prensas de la Universidad
Universidad Zaragoza

Universidad Zaragoza
1542

Tesis Doctoral

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**UNIVERSIDAD DE ZARAGOZA**
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UNIVERSITY OF ZARAGOZA

COMPUTER SCIENCE AND SYSTEM ENGINEERING DEPARTMENT

# Adaptive Mechanisms to Improve Message Dissemination in Vehicular Networks

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

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Teruel, February 2014

*To my family and my girlfriend,*
*for their patience and support.*

# Acknowledgments

I would like to sincerely thank Dr. Francisco Martinez and Dr. Piedad Garrido for supervising this thesis and giving me the opportunity to join the Intelligent Networks and Information Technologies (iNiT) Group of the University of Zaragoza. Less than 30 months ago I was talking with my friend Dr. Manuel Fogué the possibility of developing my Thesis with them and now I am going to present it. Their continuous guidance and valuable advises have strongly contributed to the quality of this work. I recognize that their example have definitely enriched me from both professional and personal aspects.

Special thanks go also to Dr. Juan Carlos Cano, Dr. Carlos T. Calafate and Dr. Pietro Manzoni for helping me in the elaboration of this thesis. The collaboration with these colleagues has been very fruitful and represented a key contribution in my thesis.

Doing research at the iNiT group has been a great experience. However, my stay at iNiT would not have been the same without all the ”zulo” colleagues I worked with over these months. I thank them for the interesting discussions and for the useful support, but most of all I express my gratitude for their sincere friendship. Thanks to them, I have always felt like home.

I would also like to remember all my close friends. I have not always been able to dedicate the right time to enjoy their company. Nevertheless, they have always been ready to show their affection and encouragement.

This thesis would not have been possible without the loving assistance of my parents. They have always supported the fulfillment of my objectives. I owe all my personal achievements to them.

Finally, I thank my girlfriend Sara. Her presence in my life is a constant incentive to continue my studies. I thank her for making every single moment spent together simply wonderful.

Julio A. Sangüesa
Teruel, February 2014

# Abstract


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, advanced electronics, and communication devices, making cars more intelligent, efficient, and safe to drive on.

The applications and advantages of using Vehicular Networks (VNs) for enhancing road safety and driving efficiency are diverse, which explains why research in this area has recently emerged. In this Thesis, we focus on Vehicular Ad-hoc Networks (VANETs), which are a particular subclass of Vehicular Networks, that involves a set of equipped vehicles communicating with each other via wireless antennas, without requiring the use of any infrastructure.

In order to enhance the warning message dissemination process, usually necessary in VANET safety applications, we propose an adaptive broadcast dissemination scheme that automatically chooses the optimal broadcast depending on the complexity of the map and the instantaneous vehicle density in the area. Its main goal is to maximize the message delivery effectiveness, while generating a reduced number of messages, and thus, avoiding or mitigating broadcast storms.

Current research on VANETs usually focuses on analyzing scenarios representing common situations with average densities. However, situations with very low or very high vehicle densities are often ignored, whereas they are very common in real vehicular environments. The aim of broadcast dissemination schemes is to maximize message delivery effectiveness, something difficult to achieve in adverse density scenarios. To address this issue, in this Thesis, we propose the *Junction Store and Forward* (JSF) and the *Neighbor Store and Forward* (NSF) dissemination schemes, specially designed to be used under low density conditions, as well as the *Nearest Junction Located* (NJL) scheme, specially developed for high density conditions.

Finally, we present a classification which includes the most relevant broadcast dissemination schemes specially designed for VANETs, highlighting their features, and studying their performance under the same simulation conditions, thus offering researchers a fair comparison. We consider that this evaluation can shed some light into the advantages and drawbacks of each solution, making it possible to determine which one is the most suitable scheme to be used in each particular scenario.

# Resumen

En el pasado, se han dedicado muchos recursos en construir mejores carreteras y autovías. Con el paso del tiempo, los objetivos fueron cambiando hacia las mejoras de los vehículos, consiguiendo cada vez vehículos más rápidos y con mayor autonomía. Más tarde, con la introducción de la electrónica en el mercado del automóvil, los vehículos fueron equipados con sensores, equipos de comunicaciones, y otros avances tecnológicos que han permitido la aparición de coches más eficientes, seguros y confortables.

Las aplicaciones que nos permite el uso de las Redes Vehiculares (VNs) en términos de seguridad y eficiencia son múltiples, lo que justifica la cantidad y recursos de investigación que se están dedicando en los últimos años. En el desarrollo de esta Tesis, los esfuerzos se han centrado en el área de las Vehicular Ad-hoc Networks, una subclase de las Redes Vehiculares que se centra en las comunicaciones entre los vehículos, sin necesidad de que existan elementos de infraestructura.

Con la intención de mejorar el proceso de diseminación de mensajes de alerta, imprescindibles para las aplicaciones relacionadas con la seguridad, se ha propuesto un esquema de difusión adaptativo, capaz de seleccionar automáticamente el mecanismo de difusión óptimo en función de la complejidad del mapa y de la densidad actual de vehículos. El principal objetivo es maximizar la efectividad en la difusión de mensajes, reduciendo al máximo el número de mensajes necesarios, evitando o mitigando las tormentas de difusión.

Las propuestas actuales en el área de las VANETs, se centran principalmente en analizar escenarios con densidades típicas o promedio. Sin embargo, y debido a las características de este tipo de redes, a menudo se dan situaciones con densidades extremas (altas y bajas). Teniendo en cuenta los problemas que pueden ocasionar en el proceso de diseminación de los mensajes de emergencia, se han propuesto dos nuevos esquemas de difusión para bajas densidades: el *Junction Store and Forward* (JSF) y el *Neighbor Store and Forward* (NSF). Además, para situaciones de alta densidad de vehículos, se ha diseñado el *Nearest Junction Located* (NJL), un esquema de diseminación que reduce notablemente el número de mensajes enviados, sin por ello perder prestaciones.

Finalmente, hemos realizado una clasificacion de los esquemas de difusión para VANETs más importantes, analizando las características utilizadas en su diseño. Además hemos realizado una comparación de todos ellos, utilizando el mismo entorno de simulación y los mismos escenarios, permitiendo conocer cuál es el mejor esquema de diseminación a usar en cada momento.

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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) [IEE10] 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.

Focusing on safety, one of the critical factors clearly stands in the fact of reducing the number of accidents and to minimize the possible injuries. When an accident occurs, vehicles will be able to send warning messages to other vehicles, preventing hazardous situations, or alert emergency services. However, high density scenarios are common in vehicular networks (especially in urban environments or in the entrance areas to the cities), and a large amount of information is expected to be transmitted between vehicles themselves and with the infrastructure units as well. Under these premises, the warning dissemination process could often suffer a serious problem due to the contention in the channel. Therefore, we believe that it would be worthy to propose new dissemination protocols for automatically sending warning messages, adapting their behavior according to environmental characteristics (e.g., the density of vehicles, the type of road in the accident, the attenuation of the wireless signal due to obstacles, etc.).

One of the most determinant factors in the dissemination process is the topology of the roadmap that affects the average distance between the sender and the receiver, as well as the different obstacles in the scenario. Another critical factor is the vehicle density, since lower densities can provoke message losses due to reduced communication capabilities, whereas higher densities can provoke a reduced message delivery effectiveness due to serious redundancy, contention, and massive packet collisions caused by simultaneous forwarding, usually known as broadcast storm [TNCS02]. Therefore, we consider that novel dissemination approaches should be proposed and tested under these adverse vehicle density conditions, thereby assessing their real performance under any circumstances.

## 1.2 Objectives of the Thesis

The main objective of this Thesis is to develop an adaptive broadcast scheme that allows each vehicle to automatically adopt the optimal dissemination scheme, fitting the warning message delivery policy to each specific scenario at any instant, and thus achieving the highest number of informed vehicles, while avoiding broadcast storm problems.

In order to implement the adaptive scheme, the second objective is to design an algorithm that selects the optimal broadcast dissemination scheme to be used for each situation. This algorithm should offer the best suitable dissemination technique to be adopted depending on current density and topology of the scenario.

Since the adaptive dissemination scheme requires to know the current vehicle density, the third objective is to allow vehicles to measure the density of their neighborhood. This Thesis should propose a method which allow vehicles to estimate the density of vehicles in real time. Unlike previous proposals, the mechanism should use several input parameters such as the number of beacons received per vehicle and the topological characteristics of the environment where the vehicles are located (number of streets, number of junctions, number of lanes, etc.).

As a fourth objective of the Thesis, we want to analyze extreme vehicle density conditions that frequently appear in VANETs. On the one hand, extremely high density conditions, which are very common in urban environments, and where the broadcast storm problem is prone to occur. On the other hand, extremely low density conditions, where the sparse environments make very difficult the spread of the warning messages. After the analysis, we want to propose broadcast dissemination algorithms specially designed to address these adverse conditions.

Finally, we will proceed to classify all the broadcast dissemination schemes studied according to the parameters used in the design of each scheme. In addition, we will make a fair performance evaluation under the same conditions, 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 make an introduction to Vehicular Networks (VNs) and Vehicular Ad Hoc Networks (VANETs), showing their main characteristics and applications. Additionally, we present the main features of the warning dissemination process, and some of the most relevant existing broadcast schemes proposed to address this issue. Finally, we classify these schemes depending of the features used in their working mode.

Chapter 3 presents our infrastructureless mechanism to estimate the vehicle density in urban environments. Unlike existing proposals, the mechanism uses as input parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located, allowing each vehicle to estimate the density of its neighborhood.

In Chapter 4 we propose RTAD, a real-time adaptive dissemination system that allows each vehicle to automatically adopt the optimal dissemination scheme to adapt the warning message delivery policy to each specific situation. Its main goal is to maximize the message delivery effectiveness while generating a reduced number of messages and, thus, avoiding or mitigating broadcast storms. As shown in that chapter, RTAD outperforms other static dissemination schemes as well as existing adaptive dissemination systems.

Chapter 5 addresses adverse vehicle density conditions in VANETs; in particular, we propose the *Junction Store and Forward* (JSF) and the *Neighbor Store and Forward* (NSF) schemes designed to be used under low density conditions, and the *Nearest Junction Located* (NJL) scheme specially developed for high density conditions.

In Chapter 6 we present a complete classification of the most relevant broadcast dissemination schemes, including our proposed approaches. In addition, we analyze the environments used by the different authors to assess their mechanisms, and we provide a comparative analysis of their performance by evaluating them under the same conditions, and focusing on the same metrics, thus providing researchers with a general overview of the benefits and drawbacks associated to each scheme.

Finally, in Chapter 7 we present a summary of the main results and contributions 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

# Background on Vehicular Networks and Warning Message Dissemination

Some years ago, 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.

## 2.1 Introduction

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).

ITS are being propelled by the development and adaptation of wireless telecommunications and computing technologies, thereby allowing our roads and highways to be both safer and more efficient transportation platforms.

The excitement surrounding vehicular networking is not only due to the applications or their potential benefits but also due to the challenges and scale of the solutions. Among technical challenges to be overcome, high mobility of vehicles, wide range of relative speeds between nodes, real-time nature of applications, and a multitude of system and application related requirements can be listed. Furthermore, considering ITS applications that require information to be relayed multiple hops between cars, vehicular networks are poised to become the most widely distributed and largest scale ad hoc networks. Such challenges and opportunities serve as the background of the widespread interest in vehicular networking by governmental, industrial, and academic bodies [KAE+11].

In this chapter we examine the impact of vehicular networks in road safety and the warning dissemination process. This chapter is organized as follows: Section 2.2 presents Vehicular Networks, and also makes an introduction to Vehicular Ad Hoc Networks (VANETs), showing their main characteristics and applications. Warning dissemination process is presented in Section 2.3, and some existing warning dissemination broadcast schemes are shown. Section 2.4 presents the simulation environment used in this Thesis. Finally, Section 2.5 concludes this chapter.

## 2.2 Vehicular Networks

Vehicular networking serves as one of the most important enabling technologies required to implement a myriad of applications related to vehicles, vehicle traffic, drivers, passengers, and pedestrians [KAE+11].

The convergence of wireless telecommunication, computing, and transportation technologies facilitates that our roads and highways can be both our transportation and communication platforms. These changes will completely revolutionize when and how we access services, communicate, commute, entertain, and navigate, in the coming future. Vehicular Networks (VNs) are wireless communication networks that support cooperative driving among communicating vehicles on the road. Vehicles act as communication nodes and relays, forming dynamic vehicular networks together with other nearby vehicles and the infrastructure [STFL10]. VNs involve vehicle-to-vehicle (V2V) [MCC+09] and vehicle-to-infrastructure (V2I) [SLCG08] communications, and have received a remarkable attention in recent years.

The specific characteristics of Vehicular Networks (VNs) favor the development of attractive and challenging services and applications, including road safety, traffic flow management, road status monitoring, environmental protection, and mobile infotainment [TML08, CSW10, AAAN13].

### 2.2.1 Vehicular ad hoc networks (VANETs)

Vehicular Ad hoc Networks (VANETs) are a particular subclass of Vehicular Networks (VNs) which represent a set of equipped vehicles communicating with each

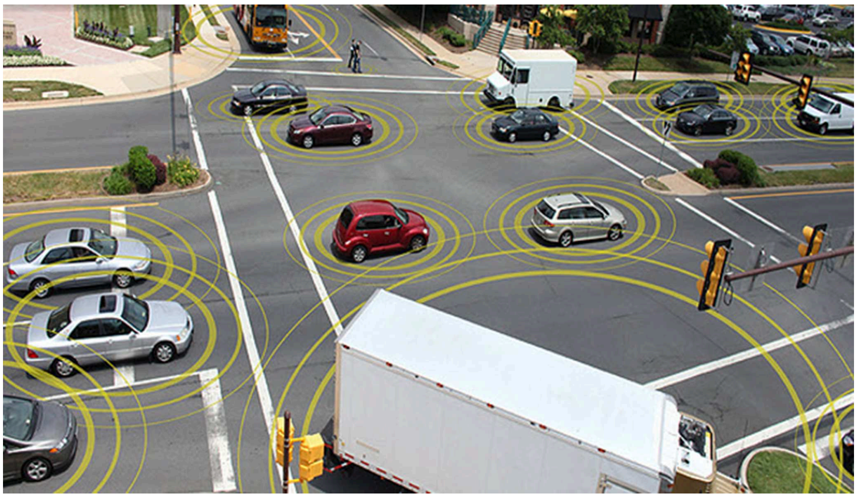


Figure 2.1: Example of a VANET [DoT14].

other via the wireless antenna, without requiring the use of infrastructure (see Figure 2.1).

VANETs are characterized by very high speed and limited degrees of freedom in nodes movement due to the road topology. A wide range of applications can be enabled in VANETs, e.g., emergency message dissemination, real-time traffic condition monitoring, collusion avoidance and safety, where communications are exchanged in order to improve the drivers responsiveness and safety in case of road incidents. VANETs not only can enhance traffic safety but also provide comfort applications between vehicles [MLP10].

In VANETs, vehicles are equipped with sensors and Global Positioning Systems (GPS) to collect information about their position, speed, acceleration, and direction to be broadcasted to all vehicles within their range. Upon receiving and processing this information, neighboring vehicles will detect and avoid potential dangers.

The research in VANETs is driven by IEEE 802.11p technology which is intended to enhance the IEEE 802.11 to support the Intelligent Transportation System applications where reliability and low latency are crucial. These applications are intended to help drivers to travel more safely and reduce the number of fatalities due to road accidents.

In IEEE 802.11p, vehicles will not send an acknowledgement (ACK) for received broadcast messages. Therefore, the transmitter could not detect the failure of the packets reception and hence will not retransmit the packet. This is a serious problem in collision warning applications where all vehicles behind the accident have to receive the warning message successfully in short time to avoid chain collisions [KAE$^{+}$11]. Vehicles can either use large transmission ranges or relay the message in a multi-hop fashion. While increasing the transmission range will increase the probability of interfering from hidden terminal nodes, using multi-hop

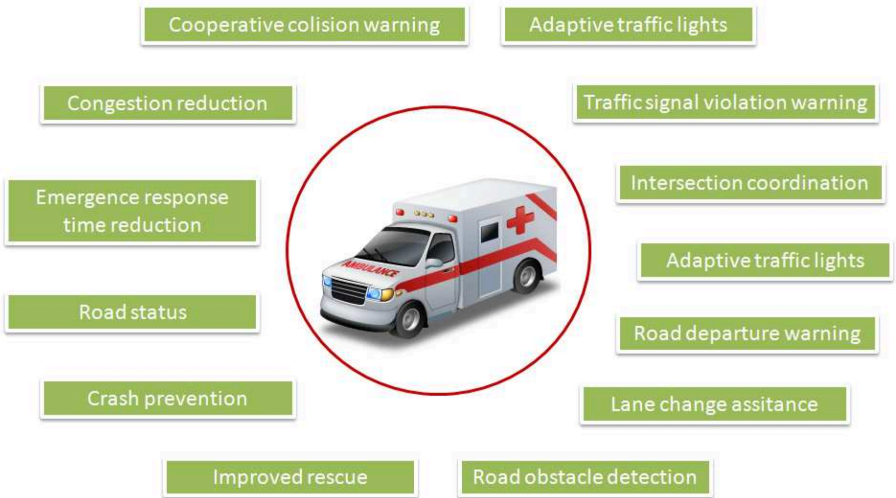



Figure 2.2: Traffic safety applications of VANETs.

communications will increase the time delay the message will encounter until it reaches its intended distance.

### 2.2.2 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 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 2.2), 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.

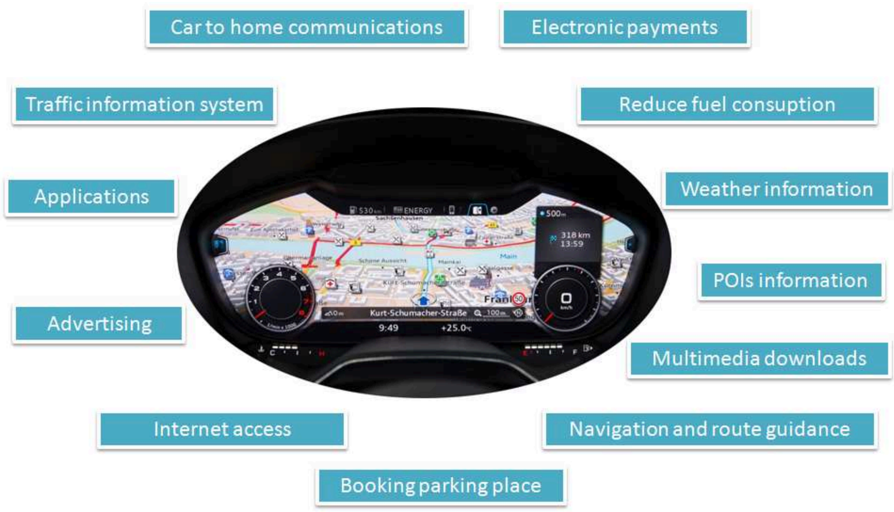



Figure 2.3: Comfort and commercial applications of VANETs.

- Comfort and Commercial applications (see Figure 2.3) 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].

## 2.3 Warning dissemination process

Regarding safety in Vehicular Networks, efficient warning message dissemination schemes are required since the main goal is to reduce the latency of such critical information while ensuring the correct reception of the alert information by nearby vehicles. When a vehicle detects an abnormal situation on the road (e.g., accident, slippery road, etc.), it immediately starts notifying the anomaly to nearby vehicles to rapidly spread the information in a short period of time. Hence, broadcasting warning messages is of utmost importance to alert nearby vehicles.

However, this dissemination is strongly affected by: (i) the signal attenuation due to the distance between sender and receiver (especially in low vehicular density areas), (ii) the effect of obstacles in signal transmission (very usual in urban areas, e.g., due to buildings), and (iii) the instantaneous vehicle density.

Regarding (i) and (ii), the topology of the roadmap is an important factor that affects the average distance between the sender and the receiver, as well as the different obstacles in the scenario. As for (iii), the warning message propagation scheme should be aware of vehicle density. In fact, lower densities can provoke message losses due to reduced communication capabilities, whereas higher densities can provoke a reduced message delivery effectiveness due to serious redundancy, contention, and massive packet collisions caused by simultaneous forwarding, usually known as broadcast storm [TNCS02].

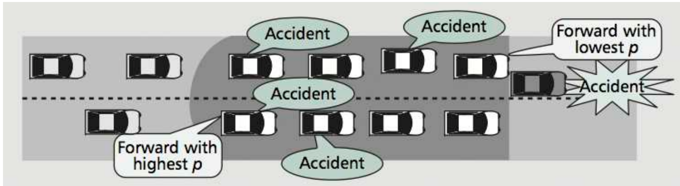



Figure 2.4: weighted p-persistence dissemination scheme example [WTP+07].

### 2.3.1 Existing Broadcast Message Dissemination Schemes

VANETs have particular features, such as distributed processing and organized networking, a great number of nodes (i.e., vehicles) moving at high speeds, a constrained but highly variable network topology, changing communication conditions and mobility patterns, building-related signal blockage, and frequent network partitioning due to the high mobility. Hence, several dissemination schemes have been proposed to improve the dissemination process according to the specific characteristics of communications in vehicular environments.

In this section, we introduce some of the most relevant broadcast schemes proposed to disseminate warning messages, e.g., in case of accident, or to advertise any critical situation on the road.

- The *Counter-based scheme* proposed by Tseng et al. [TNCS02] was initially proposed for Mobile Ad Hoc Networks (MANETs). In particular, this scheme aims at mitigating broadcast storms by using a threshold $C$ and a counter $c$ to keep track of the number of times a broadcast message is received. Whenever $c \geq C$, rebroadcast is inhibited.

- The *Distance-based scheme* [TNCS02] accounts for the relative distance $d$ between vehicles to decide whether to rebroadcast or not. When the distance $d$ between two vehicles is short, the additional coverage (AC) area of the new rebroadcast is lower, and so rebroadcasting is not recommended. Forwarding is only beneficial when the additional coverage is nearly maximum.

- The *weighted p-persistence* and the *slotted p-persistence* techniques presented by Wisitpongphan et al. [WTP+07] are some of the few rebroadcast schemes specifically proposed for VANETs. These probabilistic broadcast suppression techniques can mitigate the severity of the broadcast storms by allowing nodes with higher priority to access the channel as quickly as possible. However, their ability to avoid storms is limited since these schemes are specifically designed for highway scenarios.

  Figure 2.4 illustrates an example of weighted p-persistence working mode. Upon receiving a packet from node i, node j checks the packet ID and rebroadcasts with probability $p_{ij}$ if it receives the packet for the first time; otherwise, it discards the packet. Denoting the relative distance between nodes i and j by $p_{ij}$ and the average transmission range by R, the forwarding probability, $p_{ij}$, can be calculated on a per packet basis using the following simple expression: $p_{ij} = d_{ij}/R$.

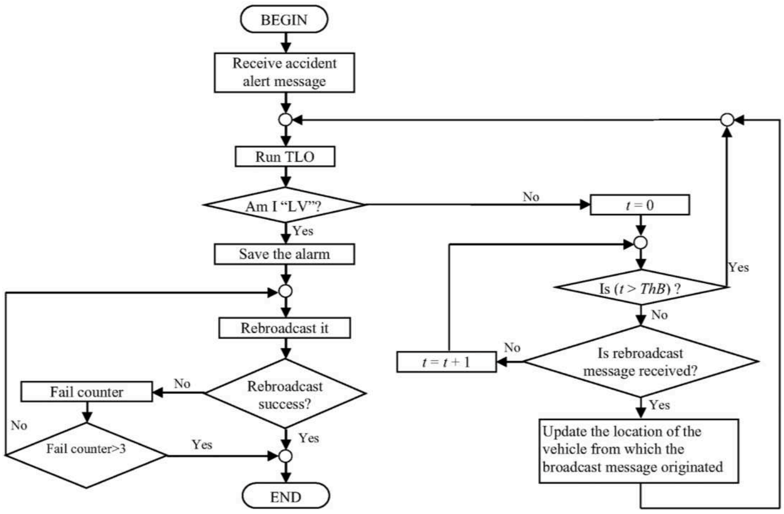



Figure 2.5: TLO dissemination scheme working flowchart [SP08].

Note that if node j receives duplicate packets from multiple sources within the waiting period of WAIT_TIME (e.g., 2 ms) before retransmission, it selects the smallest $p_{ij}$ value as its reforwarding probability; that is, each node should use the relative distance to the nearest broadcaster in order to ensure that nodes who are farther away transmit with higher probability. If node j decides not to rebroadcast, it should buffer the message for an additional WAIT_TIME + $\sigma$ ms, where $\sigma$ is the one-hop transmission and propagation delay, which is typically less than WAIT_TIME. In order to prevent message die out and guarantee 100 percent reachability, node j should rebroadcast the message with probability 1 after WAIT_TIME + $\sigma$ ms, if it does not hear the retransmission from its neighbors. Unlike the p-persistence or gossip-based scheme, weighted p-persistence assigns higher probability to nodes that are located farther away from the broadcaster given that GPS information is available and accessible from the packet header.

- The Last One (TLO) is a scheme proposed by Suriyapaibonwattana et al. [SP08] that attempts to reduce the broadcast storm problem by finding the most distant vehicle from the warning message sender, so that this vehicle will be the only one allowed to retransmit the message. This method uses GPS information from the sender vehicle and the possible receivers to calculate the distance between them.

  Figure 2.5 shows the flowchart working mode of TLO. In first place, it will check condition "Am I 'LV' " (Last Vehicle) by using GPS data. TLO algorithm will use the longitude and latitude information that is contained in the alert message and compare with position data of its own neighbor table. For example, if Accidented Vehicle (AV) has sent alert message and its position (Latitude = 40.443142, Longitude = -79.953974), the received vehicle will use AV position to find the last one. Authors used Vincenty's formula, the most accurate and widely used globally-applicable model for the earth ellipsoid base on WGS-84, to calculate distance between AV and the received vehicle. Each vehicle will calculate its distance and compare to other neighbor's distance.

Although TLO 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, the scheme does not clearly state how a node knows the position of nearby vehicles at any given time.

- The *Adaptive Probability Alert Protocol* (APAL) is an extension to the TLO scheme that uses adaptive wait-windows and adaptive probability to transmit [SPC09].

  APAL protocol is illustrated in Figure 2.6. When vehicle A is involved in an accident, it will send an alert message. This will be received by vehicles B, C, D, E, and F. All these vehicles, after receiving alert message for the first time, will start the APAL algorithm to rebroadcast the alert message. First, vehicles B, C, D, E, and F will execute step 1. They will wait until their respective $\Delta\tau_1$ expires, to decide whether to broadcast or not with probability $P_1$. Suppose that E decides to rebroadcast the alert message and does it earliest compared to other vehicles. Vehicles B, C, D, and F will receive the duplicated alert message from E, while vehicles G, H, I, and J will receive the alert message for the first time. Then vehicles G, H, I, J, and K will start APAL from step 1, and B, C, D, and F will start step 2, as they received a duplicate alert message. $P_i$ will decrease with Duplicate Number and $\Delta\tau_1$ increase. APAL decreased next broadcast probability and increased the interval $\Delta\tau_1$, because the alert message has already been disseminated. The possibility of its loss is low, though not zero. B, C, D, and F will not exit APAL protocol yet. For exiting condition, ($CountTime < \beta$ && $DuplicateNumber < \delta$) is used for improving the success rate of the alert message and prevent its loss, which may happen because the vehicles following behind are far, or transmission being poor due to bad weather, or some obstacles. Although this scheme shows even better performance than the TLO scheme, it was also only validated in highway scenarios.

- Slavik and Mahgoub [SM10] proposed a stochastic broadcast scheme (SBS) to achieve an anonymous and scalable protocol where relay nodes rebroadcast messages according to a retransmission probability. The performance of the SBS system depends on the vehicle density, and the probabilities must be tuned to adapt to different scenarios. However, the authors only test this scheme in an obstacle-free environment, thus not considering urban scenarios where the presence of buildings could interfere with the radio signal.

- The *enhanced Street Broadcast Reduction* (eSBR) scheme, proposed by Martinez et al. [MFC+10], was specially designed to be used in VANETs, taking advantage of the information provided by maps and built-in positioning systems, such as the GPS. Vehicles are only allowed to rebroadcast messages if

```
When Receive Alert message
 IF (Receive alert message for First time)
     Δτ_i Random between 1 – 100ms
     P_i random probability between 0.7 – 0.9
 END IF
 CountTime =0
 DuplicateNumber=0
WHILE (CountTime < β && DuplicateNumber < δ)
 WHILE (Δτ_i is not expired)
       Listen for duplicate alert message
       Count = number of received duplicate alert message
 END WHILE.
   IF (received duplicate alert message)
     DuplicateNumber = DuplicateNumber + Count
     P_{i+1} = P_i/DuplicateNumber
     Δτ_{i+1} = Δτ_i * DuplicateNumber
   ELSE
     Rebroadcast with P_i
        IF (Rebroadcast is successful)
           P_{i+1} = P_i/2
           Δτ_{i+1} = Δτ_i
        ELSE
           P_{i+1} = P_i*2; P_{i+1} is clipped to 1;
           Δτ_{i+1} = Δτ_i/2
        END IF.
   END IF.
 CountTime = CountTime + Δτ_i
END WHILE
```

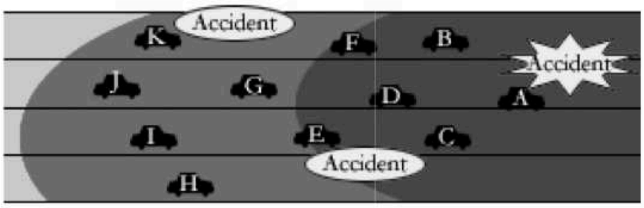



Figure 2.6: APAL dissemination scheme working algorithm [SPC09].

they are located far away from their source ($> d_{min}$), or if the vehicles are located in different streets, giving access to new areas of the scenario. The eMDR scheme uses information about the roadmap to avoid blind areas due the presence of urban structures blocking the radio signal.

Figure 2.7 shows the algorithms used by the eSBR scheme, where *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 an 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 Pb indicates the priority of the normal messages. When *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). When a new message $m$ 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.

Authors 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 to an intersection. Hence, warnings can be rebroadcasted to vehicles which are traveling on other streets, overcoming the radio signal interference due to the presence of buildings. If the message is a beacon, it is simply discarded since we are not interested in the dissemination of beacons.

- Fogue et al. [FGM+12b] presented the *enhanced Message Dissemination for Roadmaps* (eMDR) scheme, as an improvement to eSBR. In particular, eMDR increases the efficiency of the system by avoiding to forward the same message multiple times if nearby vehicles are located in different streets. Specifically, vehicles use the information about the junctions of the roadmap, so that only the closest vehicle to the geographic center of the junction, according to the geopositioning system, is allowed to forward the received messages. This strategy aims at reducing the number of broadcasted messages while maintaining a high percentage of vehicles informed.

  Figure 2.8 summarizes the eMDR working mode, where $v_s$ is the sender vehicle, $v_r$ is the receiver vehicle, $j$ is a junction of the roadmap, $d$ represents a geographical distance function, $d_{min}$ is the minimum rebroadcast distance and $th_j$ is the threshold representing a junction's influence range.

- The connected dominating set (CDS) proposed by Ros et al. [RRS09] is a

**Algorithm 1.** eSBR_Send()

```
Pw = AC3;     // set the highest priority
Pb = 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 = Pw;
        set m.seq_num = ID++;
        broadcast warning message (m);
        sleep (Tw);
    else
        create message m;
        set m.priority = Pb;
        broadcast beacon (m);
        sleep (Tb);
```

**Algorithm 2.** eSBR_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 2.7: eSBR dissemination scheme working algorithms [MFC+10].

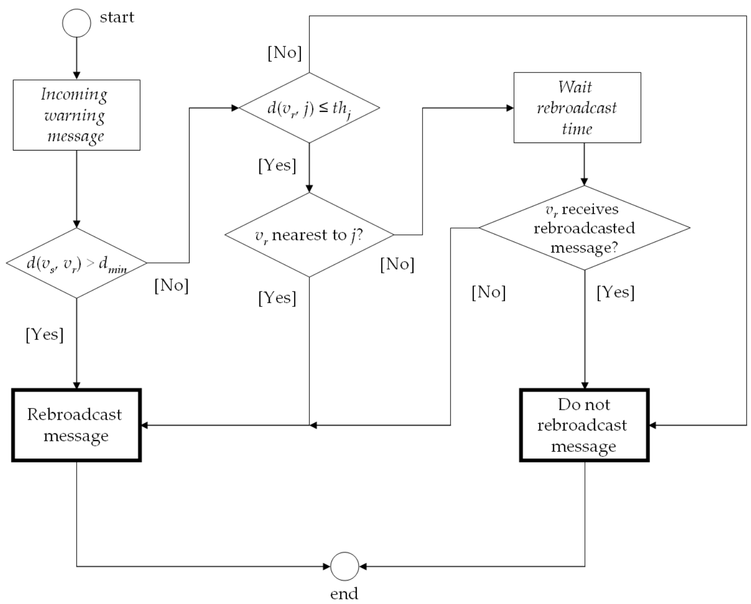



Figure 2.8: eMDR dissemination scheme working flowchart [FGM+12b].

fully-distributed adaptive algorithm suitable for different vehicular scenarios and traffic conditions. It does not depend on threshold values nor different internal states which vary the protocol behavior. Each vehicle decides by itself whether to forward a received broadcast message or not. Such decision is solely based on the local information which the vehicle has acquired from its neighborhood by means of periodic beacon messages. This guarantees ultimate scalability. For its implementation, beacons contain the position of the sender and (additionally) identifiers of the recently received broadcast messages, which serve as acknowledgements of reception. Applying a heuristic for computing connected dominating sets and the neighbor elimination scheme, the protocol makes the forwarding decision trying to minimize the number of transmissions while maximizing the reliability of the broadcast task. Its target is to improve the protocol efficiency in VANET scenarios. The major changes and improvements made include using broadcast message acknowledgements to avoid redundant retransmissions and improve reliability employing just 1-hop position information. The algorithm requires adding the list of all neighbors to the beacons, increasing message size and leading to the increase of collisions and message failures.

- Sommer et al. [STD11] presented the Adaptive Traffic Beacon (ATB), a fully distributed message dissemination protocol which uses adaptive beaconing based on two key metrics: message utility and channel quality. Authors showed that adaptive beaconing leads to a much broader dissemination of messages (in terms of penetration rate) than flooding-based approaches, although at a slower rate. The main objective of ATB is to exchange information in knowledge bases by sending beacons as frequently as possible, while maintaining a congestion-free wireless channel.

  The knowledge base stores only the most recent information for each route segment, i.e., each new event either updates an existing record or it is appended to the knowledge base. A garbage collection process continuously expunges entries that are older than a configurable timeout. Each node prioritizes available information according to the age of an entry, as well as the distance to the event. Using the calculated priorities, a node can then generate beacon messages by selecting as many entries as there is room in a single link layer frame from the top of the list, i.e., those with the highest priority. The most important message is used to calculate the message priority for the beacon interval. This way, the frame size is optimally used and problems with stateful handling of messages split into multiple frames are inherently avoided. Nodes that receive these beacons can then in turn update their knowledge bases and beacon intervals according to the algorithm illustrated in Figure 2.9.

- Bi et al. [BCSZ10] proposed the Cross Layer Broadcast Protocol (CLBP), a dissemination scheme that uses a metric based on channel conditions, geographical locations, and vehicles' speed, to select an appropriate relaying vehicle. This scheme also supports reliable transmissions exchanging *Broadcast Request To Send* (BRTS) and *Broadcast Clear To Send* (BCTS) frames.

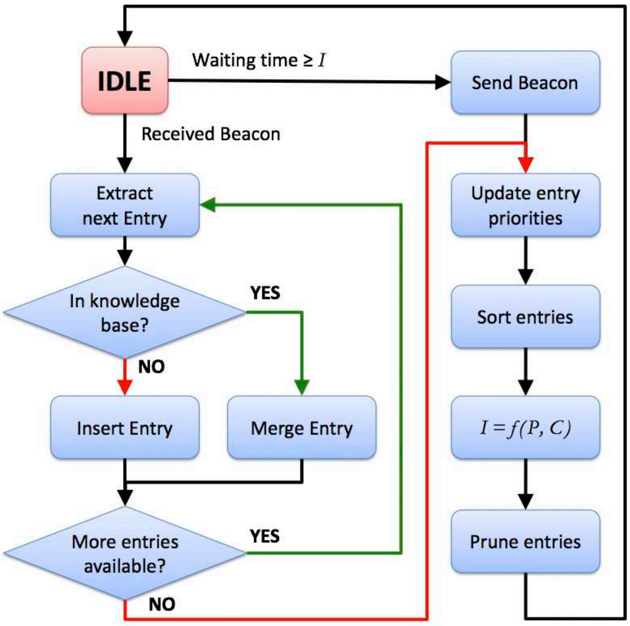



Figure 2.9: ATB dissemination scheme working flowchart [STD11].

CLBP reduces the transmission delay, but it is only conceived for single-direction environments (like highway scenarios), and its performance in urban environments has not been tested.

- Sou and Lee [SL12] proposed the Store-Carry-Broadcast (SCB) scheme, which assists message dissemination by broadcasting over a specific road segment instead of a single vehicle. In the SCB scheme, an opposite vehicle helps to disseminate the safety messages to oncoming vehicles traveling on the reverse lane by broadcasting. Compared with the well-known store-carry-forward scheme in VANETs, the SCB scheme consumes much less network bandwidth in terms of the number of broadcasts performed.

  Figure 2.10 illustrates the detailed routing flow algorithm for the SCB scheme. According to the authors, SCB algorithm exhibits several advantages compared to previous proposals: First, the opposite vehicle X can greedily achieve an effective range with a road-level length of 2R to disseminate a message for more destination nodes traveling on the reverse lane. Second, an automatic SCB repetition is performed when a broadcast groups tail ($V_k$) and the next destination vehicle ($V_k$+1) are disconnected. Third, a better eastbound vehicle can be automatically selected as the next SCB forwarder (X) due to the nature of wireless broadcast. Note that there is a two-hop broadcast overhead incurred in the SCB initiation and only one-hop broadcast overhead for that in the SCB repetition. The SCB repetition is used to avoid unnecessary relay hops incurred in spare VANETs.

- Tonguz et al. [TWB10] presented the Distributed Vehicular Broad-CAST

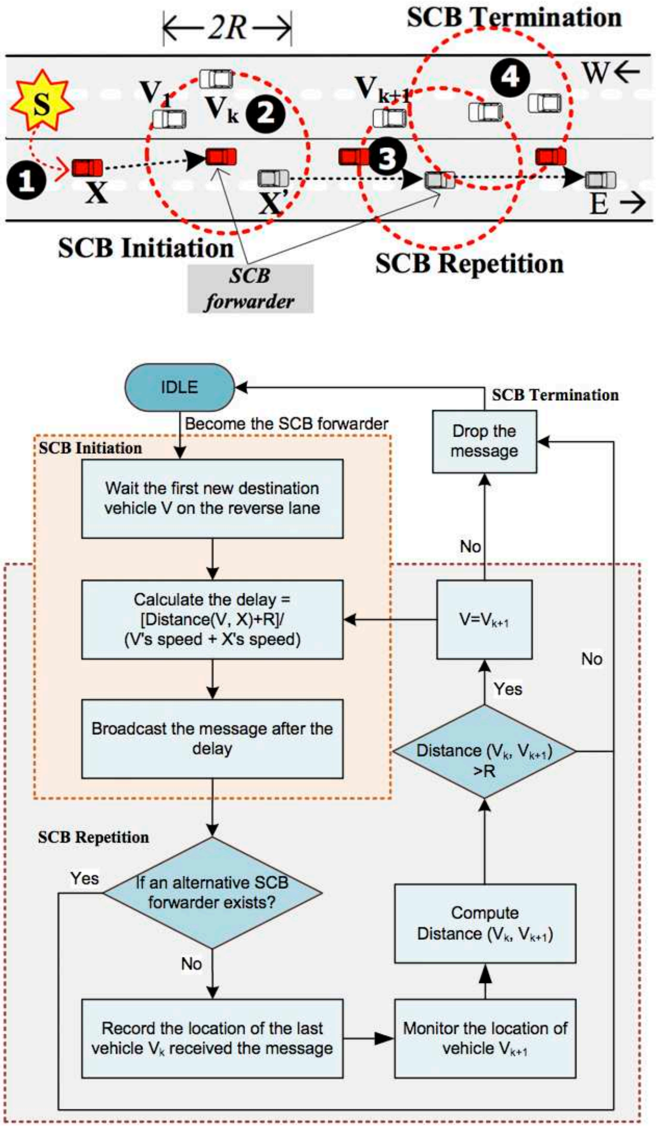



Figure 2.10: SCB dissemination scheme working flowchart [SL12].

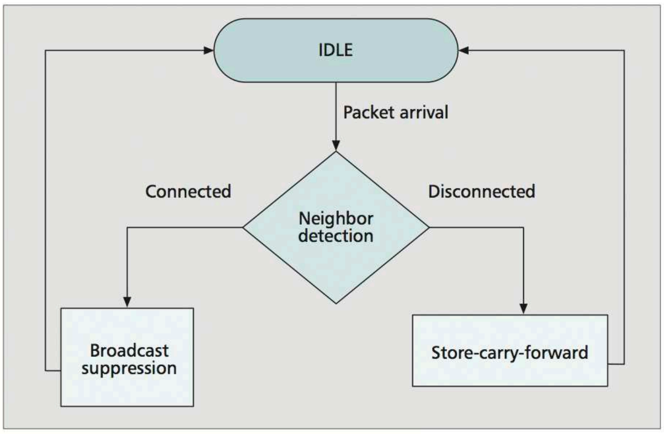



Figure 2.11: DV-CAST dissemination scheme working flowchart [TWB10].

(DV-CAST) protocol. Specifically, DV-CAST is a distributed broadcast protocol that relies only on local neighbor information for handling broadcast messages in VANETs. DV-CAST mitigates the broadcast storm and the disconnected network problems simultaneously, while incurring a small amount of additional overhead.

As illustrated in Figure 2.11, the DV-CAST protocol relies on local density information (i.e., a list of one-hop neighbors) as the main criterion to determine how to handle message rebroadcasting, adapting the dissemination process depending on the density of neighbor vehicles, their position, and their direction.

- Viriyasitavat et al. [VTB11] proposed the Urban Vehicular broadCAST (UV-CAST) protocol to reduce the broadcast storm problem while solving disconnected network problems in urban VANETs.

  Figure 2.12 shows the working flowchart of UV-CAST, As shown, the algorithm selects different mechanisms for message dissemination in VANETs, differentiating between well-connected and disconnected network regimes. Vehicles in well-connected regimes rebroadcast incoming messages after a waiting time if no redundant messages are received. Vehicles under disconnected regimes must decide if they are suitable for the Store-Carry-Forward (SCF) task, forwarding the message whenever they meet new neighbors. The SCF task is assigned to vehicles that have a small expected time before they detect new neighbors, obtained as the boundary vehicles of the neighbors within communication range.

  UV-CAST is a completely distributed broadcast protocol and it can be implemented by using only the local information available to each vehicle in an urban VANET. The protocol is designed by taking into account the two-dimensional road topology in urban settings. In contrast to one-dimensional highway scenarios, routing protocol design in urban areas is a much more challenging task for many reasons: (i) direction of vehicles in urban areas

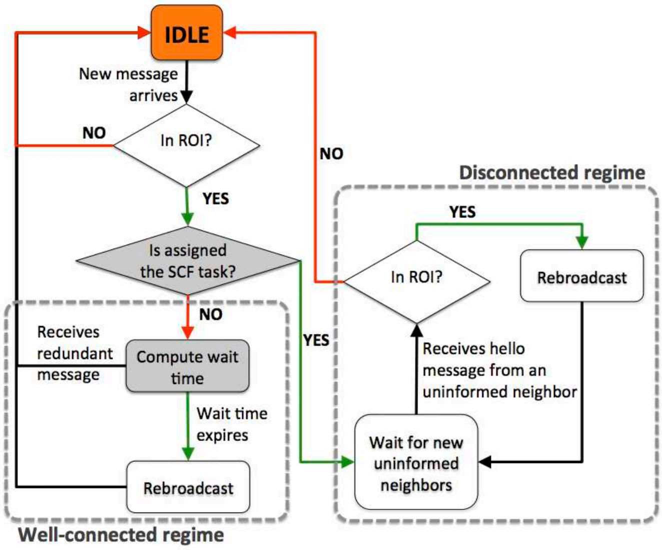



Figure 2.12: UV-CAST dissemination scheme working flowchart [VTB11].

may change at intersections while direction of vehicles on highways do not change until they leave the highway; (ii) while a message in highway scenarios is disseminated in only one direction, message dissemination direction in urban areas may encompass 360 degrees. Thus, the majority of the existing broadcast protocols designed for highway VANETs cannot be applied to urban settings. The performance of the UV-CAST protocol has been evaluated in terms of reachability, received distance, and network overhead in a regular Manhattan Street scenario, as well as in a real city (Pittsburgh, PA). While the proposed UV-CAST protocol assumes no infrastructure support, it can also utilize infrastructure support whenever it exists. Such infrastructure support could further enhance the performance of the UV-CAST protocol.

- Sormani et all. [STC+06] defined a message propagation function that encodes information about both target areas and preferred routes. Then, they showed how this function can be exploited in several routing protocols. Specifically, they proposed the Function-Driven Probabilistic Diffusion (FDPD), a probabilistic message dissemination scheme that uses a propagation function calculated by means of the distance between sender and receiver, to determine the forwarding vehicles and reduce the broadcast storm problem.

  The core mechanism of FDPD is described in Figure 2.13. As shown, the scheme needs to map the gain associated to forwarding a message onto a [0,1] interval. This gain is referenced with the difference between the evaluation of the propagation function at the sende's and receiver's position. Additionally, to normalize this quantity, authors introduce the notion of best point (see Equation 2.1). The best point is the physical location within the communi-

**Pseudocode** *Function Driven Probabilistic Diffusion (FDPD)*: on receiving message $m$.

```
Function f ← m.PropagationFunction
if neverSeen(m)
∧f(localPosition) < f(m.SenderPosition) then
    BestPoint ←
      best(f, m.SenderPosition, m.SenderCommRadius)
    Probability p ←
      (f(m.SenderPosition) − f(localPosition)) / (f(m.SenderPosition) − f(BestPoint))
    if randomChoice(p) then
        m.SenderPosition ← localPosition
        sendBroadcast(m)
    end if
end if
```

Figure 2.13: FDPD dissemination scheme working algorithm [STC+06].

cation radius of the sender node where the propagation function returns the lowest value.

$$best(f, p, r) = min(f(X)), X \in D(p, r) \tag{2.1}$$

where D(p, r) is the physical space covered by the communication radius $r$ of the sender node when in position $p$. Given the above definition, one can normalize the aforementioned difference with the difference between the evaluation of the propagation function at the best point and the same evaluation at the sender's positions.

### 2.3.2 Classification of the Dissemination Schemes

In vehicular networks, most dissemination schemes alleviate the broadcast storm problem by inhibiting certain vehicles from rebroadcasting using different parameters, reducing message redundancy, channel contention, and message collisions.

Figure 2.14 shows the proposed classification of the broadcast dissemination schemes previously presented. In particular, we classified them according to the different characteristics and techniques they use to determine whether a vehicle is allowed to rebroadcast a message (i.e., beacon-based, topology-based, distance-based, flooding-based, store-and-Forward techniques, and probabilistic-based). Next, we present them in detail:

- **Flooding**. This strategy is the simplest broadcast scheme, in which vehicles blindly rebroadcast every message. We consider that the counter-based dissemination scheme is part of this group (i.e., a limited flooding), since this approach, used to mitigate broadcast storms, 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.

- **Beacon**. In vehicular networks, similarly to other wireless networks, *beacons* are messages sent by vehicles with information regarding their positions, speed, etc. When using safety applications, these periodic messages have lower priority than warning messages, and so they are not propagated by

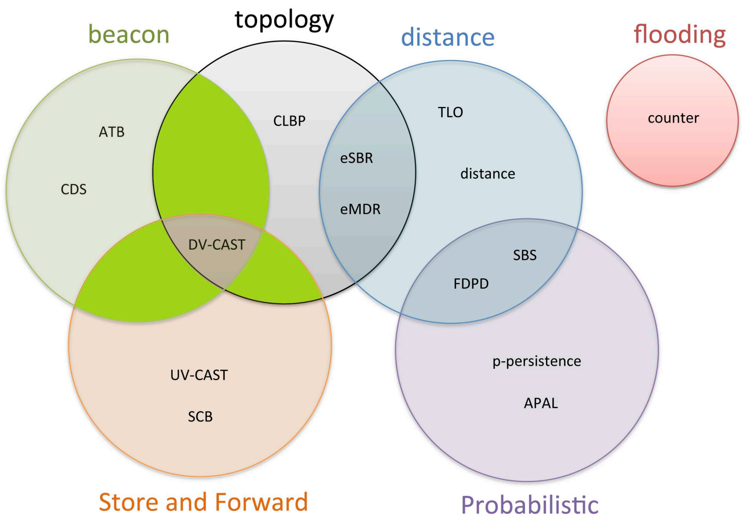



Figure 2.14: Venn diagram classifying the broadcast dissemination schemes presented in Section 2.3.1 according to the dissemination policy adopted.

other vehicles. The information contained by these messages could be used to improve the knowledge about the surrounding area of each vehicle, taking decisions accordingly. In this category, we found several proposed schemes such as ATB, CDS, and DV-CAST. All of them use the received beacons to determine whether to rebroadcast a message.

- **Topology**. The topology of the roadmap constrains cars' movements, so it is an important factor accounting for mobility in simulations. Moreover, it affects the average distance between the sender and the receiver, as well as the different obstacles present in the scenario. Considering that the impact of buildings and other urban obstacles on the wireless signal propagation is of utmost importance in realistic urban scenarios, the information about the road topology is used to maximize the dissemination performance, and only vehicles placed at suitable locations are usually allowed to forward messages. Several broadcast dissemination schemes, such as CLBP, eSBR, eMDR, and DV-CAST, use information regarding topology to improve the dissemination process.

- **Distance**. According to this technique, vehicles use the relative distance $d$ between them to decide whether to rebroadcast a message. 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 [TNCS02]. If $d$ is larger, the additional coverage will also be larger, increasing the usefulness of messages forwarded under these circumstances. Several proposed schemes, such as TLO, distance-based, SBS, eSBR, eMDR, and FDPD, fall into this category.

- **Store and Forward**. In this technique, a vehicle, after receiving a new warning message, stores it, and then it waits to rebroadcast the message until a criterion, which determines when the package should be sent, is fulfilled. According to this technique, the vehicle usually waits to rebroadcast the message until a new neighbor is found, trying to maximize the performance, especially in sparse environments. Several proposed schemes, such as UV-CAST, SCB, and DV-CAST belong to this category.

- **Probabilistic**. The schemes included in this category require using probabilistic distributions to determine the probability of broadcasting a given message, depending on the conditions of the decision vehicle. Most of the schemes that fall in this category make use of the Gaussian or the uniform distribution to associate a probability to each message or vehicle. In this category, we found several proposed schemes such as FDPD, SBS, APAL, and p-persistence approaches.

As shown, most of the existing broadcast schemes only account for a specific characteristic, or only consider a single technique (e.g., ATB, CDS, UV-CAST, SCB, or distance-based). However, other solutions such as DV-CAST, eSBR, eMDR, and FDPD combine two different elements to improve performance (e.g., beacons and topology, topology and store-and-forward techniques, distance and probabilistic functions, etc.). In general, this approach seems to be better since the more information is used to determine whether to rebroadcast a message, the higher is the probability of making the optimal decision.

Figure 2.14 also shows that there are some areas where there is no broadcast dissemination scheme yet proposed. Therefore, in this Thesis, we focus our efforts to develop novel dissemination schemes that will cover these gaps.

## 2.4 Simulation Environment, Methodology, and Metrics

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]. Fortunately, the increasing popularity and attention to VANETs has prompted researchers to develop accurate and realistic simulation tools.

Simulation results presented in this Thesis were obtained using the ns-2 simulator [FV00], modified to consider the IEEE 802.11p standard[1].

[1] All these improvements and modifications are available at http://www.grc.upv.es/software/

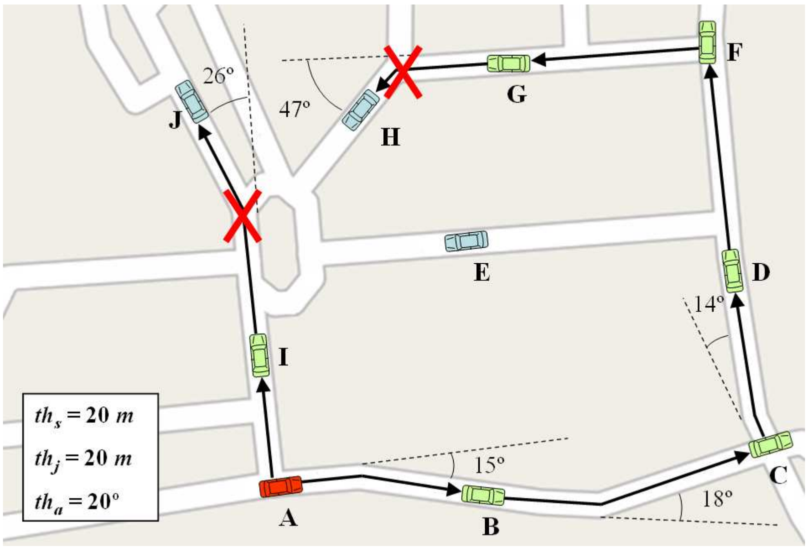



Figure 2.15: Example of visibility in RAV.

Ns-2 simulator 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).

In terms of the physical layer, the data rate used for packet broadcasting in our simulations is 6 Mbit/s, as this is the maximum rate for broadcasting in 802.11p. The MAC layer was also extended to include four different channel access priorities. Therefore, application messages are categorized into four different Access Categories (ACs), where AC0 has the lowest and AC3 the highest priority.

The purpose of the 802.11p standard is to provide the minimum set of specifications required to ensure interoperability between wireless devices when attempting to communicate in potentially fast-changing communication environments. For our simulations, we chose the IEEE 802.11p because it is expected to be widely adopted by the industry.

The simulator was also modified to make use of the *Real Attenuation and Visibility* (RAV) radio propagation model [MFT+13].

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. 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, RAV basically states whether two different vehicles are in line-of-sight.

Figure 2.15 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. RAV is proved to increase the level of realism in VANET simulations using real urban roadmaps in the presence of obstacles.

As for vehicular mobility, it has been obtained with CityMob for Roadmaps (C4R) [FGM$^+$12a], which was proposed to simulate more realistic vehicular scenarios based on real roadmaps from all over the world. C4R relies on both the OpenStreetMap [Ope12] tool to get the real roadmaps, and SUMO [KEBB12] to generate the vehicles and their movements within these scenarios. OpenStreetMap (OSM) is a collaborative project to create a free editable map of the world, which is being built largely from scratch, and released with an open content license. The Simulation of Urban MObility (SUMO) is an open source, microscopic, space-continuous traffic simulator designed to handle large road networks. C4R is able to import maps directly from OpenStreetMaps, and make them available for being used by the ns-2 simulator.

With regard to data traffic in our simulations we consider that vehicles operate in two modes: (a) warning mode, and (b) normal mode. Warning mode vehicles inform other vehicles about their status by sending warning messages periodically with the highest priority (AC3) at the MAC layer; each vehicle is only allowed to propagate them once for each sequence number. Normal mode vehicles enable the diffusion of these warning packets and, periodically, they also send *beacons* with information such as their positions, speed, etc. These periodic messages have lower priority (AC1) than warning messages, and so they are not propagated by other vehicles.

Along this document, several metrics will be used to measure the performance of the different proposals. In particular, we are interested in the following performance metrics:

- **Percentage of informed vehicles:** This metric represents the percentage of vehicles that receive the warning messages sent by warning mode vehicles. During the warning message dissemination process, the most important objective to accomplish consists on informing the highest number of vehicles in the shortest time possible, thereby we consider that this metric is a key factor to assess the dissemination process.

- **Number of messages received per vehicle:** This metric represents the number of messages received per vehicle, including beacons and warning messages. In particular, it gives an estimation of channel contention, and of the overhead of the dissemination scheme.

  The number of messages produced by a given dissemination scheme may become very important in VANETs due to the high number of messages sent and received by the vehicles involved in the communication process. This could increase channel contention and the frequency of collisions.

- **Warning notification time:** This is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle. This metric indicates the time evolution of the dissemination process. Since several schemes could achieve a similar percentage of informed vehicles, the time required to achieve this could be critical, especially in safety applications.

## 2.5 Summary

Vehicular networking is the enabling technology that will support several applications varying from global Internet services and applications up to active road safety applications. In this chapter we introduced and discussed the possible applications and use cases that could be supported by vehicular networks in the near and long term future, focusing on safety applications, that look for increasing the safety of passengers.

Since safety applications based on vehicular communications rely on the dissemination of warning messages, we presented in detail the warning message dissemination process, and analyzed the most relevant existing proposals in this field. In addition, we analyzed the features used by different schemes in their design, offering a state-of-the-art of existing works.

Finally, we presented the most important characteristics of the simulation environment, the methodology followed, as well as the metrics used in all the simulations presented along this Thesis.

# Chapter 3

# Real-Time Density Estimation

In Vehicular Networks, communication success usually depends on the density of vehicles, since a higher density allows having shorter and more reliable wireless links. Thus, knowing the density of vehicles in a vehicular communications environment is important, as better opportunities for wireless communication can show up. However, vehicle density is highly variable in time and space. This chapter deals with the importance of predicting the density of vehicles in vehicular environments to take decisions for enhancing the dissemination of warning messages between vehicles. In particular, we propose a novel mechanism to estimate the vehicular density in urban environments. Our mechanism uses as input parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located. Simulation results indicate that, unlike previous proposals solely based on the number of beacons received, our approach is able to accurately estimate the vehicular density, and therefore it could support more efficient dissemination protocols for vehicular environments, as well as improve previously proposed schemes.

## 3.1 Introduction

The specific characteristics of vehicular networks favor the development of attractive and challenging services and applications. Though traffic safety has been the primary motive for the development of these networks [STMZI+10, RKM+10, GMASVR+12], VNs also facilitate applications such as managing traffic flow, monitoring road conditions, environmental protection, and mobile infotainment applications [LGSGS+11, MCCF13, PnLM+12]. Most of these applications could be more efficient if the protocols involved become aware of the density of vehicles at any given time [MBML11], being able to adapt their behavior according to this factor. Thus, knowing the traffic density in vehicular scenarios is of great importance since it promotes the more efficient use of the wireless channel [SHG09].

One issue to keep in mind when making any proposal related to vehicular networks is to study in detail how it behaves when modifying all the possible factors [MTC+11]. However, this can be a very time-consuming task, so it is recommended to focus only on the most important factors, overlooking the rest of the parameters. Fogue *et al.* [FGM+11] concluded that the most significant factors affecting communication in realistic urban environments are: (i) the density of vehicles, since messages are propagated much more easily in high density scenarios than in scenarios with a low vehicle density (where messages cannot exploit the inherent multihop capabilities of VNs), and (ii) the urban topology, since the presence of buildings greatly affects the wireless signal propagation.

Traditionally, in Transportation Systems, vehicle density has been one of the main metrics used for assessing the road traffic conditions. A high vehicle density usually indicates that the traffic is congested. Currently, most of the vehicle density estimation techniques are designed for using infrastructure-based traffic information systems. Hence, these approaches require the deployment of vehicle detecting devices such as inductive loop detectors, or traffic surveillance cameras [TC07, JHGBGR10]. Consequently, these approaches do not exploit the capabilities offered by the emerging self-organizing vehicular traffic information systems, where vehicles are able to collect and process the traffic information without relying on any fixed infrastructure.

In this chapter we focus on the vehicle density awareness in urban environments, and we present a solution to estimate the density of vehicles based on the number of beacons received per vehicle, and the roadmap topology. We consider that vehicles, able to precisely estimate the vehicular density in their neighborhood, can adjust their diffusion scheme according to this density. When using our density estimation proposal, an adaptive system could increase successful communication probability in sparse networks by increasing its data dissemination rate, or reduce the channel contention in high density scenarios by reducing the number of broadcast messages.

The chapter is organized as follows: in Section 3.2 we review previous works closely related to our proposal, highlighting the similarities and differences. In Section 3.3 we present in detail our proposal for real-time estimation of vehicular density. In Section 3.4 we measure the estimated error to assess the goodness of our proposal. In Section 3.5 we compare our proposal with a density estimation method that only relies on the information provided by the beacons received. Finally, in Section 3.6 we present the main conclusions of this chapter.

## 3.2 Related Work

Despite the importance of determining the vehicular density to improve the support for vehicular network applications, so far there have not been enough studies that explored the density estimation in order to improve wireless communications in vehicular environments. Next, we will discuss the most relevant works in this field. Tyagi *et al.* [TKK12] considered the problem of vehicular traffic density estimation, using the information provided by the cumulative acoustic signal acquired from a roadside-installed single microphone. This cumulative signal comprises several noise signals such as tire noise, engine noise, engine-idling noise, occasional honks, and air turbulence noise of multiple vehicles. Based on these distributions, they used a Bayes classifier to classify the acoustic signal segments. Using a discriminative classifier, such as a support vector machine (SVM), results in further classification accuracy gained over the Bayes classifier. This mechanism requires to deploy microphones in every street to be able to estimate the vehicular density.

Tan and Chen [TC07] proposed a novel approach of combining an unsupervised clustering scheme called AutoClass with Hidden Markov Models (HMMs) to determine the traffic density state in a Region Of Interest (ROI) of a road in a traffic video. This approach requires to deploy video cameras in every street to be able to estimate the vehicular density, and it involves huge computational requirements.

Shirani *et al.* [SHG09] presented the Velocity Aware Density Estimation (VADE) approach. In VADE, a car estimates the density of neighboring vehicles by tracking its own velocity and acceleration pattern. An opportunistic forwarding procedure, based on VADE estimation, was also proposed. In this procedure, data forwarding is done when the probability of having a neighbor is high, which dramatically reduces the probability of messages being dropped. This approach can be very inaccurate since the own velocity and acceleration pattern of a vehicle traveling in a city do not seem very representative when accounting for the vehicular density in the nearby roads.

Artimy [Art07] proposed a scheme that allows vehicles to estimate the local density, and distinguish between the free-flow and the congested traffic phases. The density estimation is used to develop a dynamic transmission-range assignment (DTRA) algorithm that adjusts the vehicle transmission range dynamically, according to the local traffic conditions. Similarly to the previous work, the scheme presented in this chapter is based on the flow-density relationship, which seems to be only applicable to simple topologies such as highways. Maslekar *et al.* [MBML11] claimed that clustering has demonstrated to be an effective concept to implement the estimation of vehicular density in the surroundings. In this work, they proposed a direction based clustering algorithm with a clusterhead switching mechanism. This mechanism aims at overcoming the influence of overtaking within the clusters. The proposed algorithm facilitates the attaining of better stability, and thus improves the density estimation within the clusters. Simulation results showed that the proposed clustering algorithm is rendered stability through the switching mechanism, and hence provides a better accuracy in terms of density estimation. However, due to high mobility, a stable cluster within a vehicular framework is difficult to implement.

Stanica *et al.* [SCB11] considered that the medium access control protocol of a future vehicular ad-hoc network is expected to cope with highly heterogeneous conditions. An essential parameter for protocols issued from the IEEE 802.11 family is the minimum contention window used by the back off mechanism. While its impact has been thoroughly studied in the case of wireless local area networks, the importance of the contention window has been somehow neglected in the studies focusing on vehicle-to-vehicle communication. In this paper, authors showed that the adjustment of the minimum contention window depending on the local node density can notably improve the performance of the 802.11 protocol. Moreover, they compared through simulation in a realistic framework five different methods for estimating the local density in a vehicular environment, presenting the advantages and the shortcomings of each of them. Venkata *et al.* [VPPM11] proposed a clustering approach for traffic monitoring and routing, where the Cluster Head (CH) election is done based on distance and direction information. Since clusters are formed all along the road, CH's will take the responsibility of routing the message to the destination. Simulation results showed better stability, accurate density estimation in the cluster, better end-to-end delay, and good packet delivery ratio. However, the density estimation mechanism operation is limited to the vehicles within the cluster.

Other authors use the Kalman filtering technique for the estimation of traffic density. For example, Balcilar and Sonmez [BS08] estimate traffic density based on images retrieved from traffic monitoring cameras operated by the Traffic Control Office of Istanbul Metropolitan Municipality. To this end, they use a Kalman filter-based background estimation, which can efficiently adapt to environmental factors such as light changes. However, this approach requires the density estimation procedures to be applied to the road areas manually marked beforehand. More recently, Anand *et al.* [AVS11] proposed a method that also uses the Kalman filtering technique for estimating traffic density. In particular, they propose using the flow values measured from video sequences and the travel time obtained from vehicles equipped with a Global Positioning System (GPS). They also report density estimation using flow and Space Mean Speed (SMS) obtained from location-based data, using the Extended Kalman filter technique.

All of these works established the importance of vehicular density awareness for neighboring areas, but none has deepened in the analysis of the accuracy of the method used to estimate this density, the best time period to gather the required data, or the effect of the topology in the results obtained. In most cases, this estimation does not take place in real time or requires infrastructure deployment. Moreover, most of the works regarding the use of Vehicular Networks only use the number of beacons to estimate the vehicular density. In this chapter, we demonstrate how existing approaches can be highly inaccurate, since the characteristics of the simulated roadmap can significantly affect the obtained results, making the estimation erroneous.

## 3.3 Real-Time Vehicular Density Estimation

The main objective of this chapter is to propose a mechanism that allows estimating the density of vehicles in a specific area by using Vehicular Networks. In particular, we intend to estimate the vehicular density taking into account the number of beacons received and the topological features of the selected area (which can be obtained from the in-vehicle GPS unit).

Our method consists of three phases. In the first phase, we first analyze the features of different cities (see Section 3.3.1). During the second phase, the vehicles obtain the number of beacons received (see Section 3.3.2). Finally, in the third phase, each vehicle can estimate the vehicular density in its neighborhood by applying an equation that requires as input parameters the values, in terms of

Table 3.1: Map features.

| **Map** | **Streets** | **Junctions** | **Avg. St. Length** | **Lanes/Street** | **SJ Ratio** |
|---|---|---|---|---|---|
| Rome | 1655 | 1193 | 77.0296 m. | 1.0590 | 1.3873 |
| Rio de Janeiro | 542 | 401 | 167.9126 m. | 1.1135 | 1.3516 |
| Valencia | 2829 | 2233 | 60.7434 m. | 1.0854 | 1.2669 |
| Sydney | 872 | 814 | 138.0716 m. | 1.2014 | 1.0713 |
| Amsterdam | 1494 | 1449 | 90,8164 m. | 1.1145 | 1.0311 |
| Madrid | 628 | 715 | 183.4947 m. | 1.2696 | 0.8783 |
| San Francisco | 725 | 818 | 171.4871 m. | 1.1749 | 0.8863 |
| Los Angeles | 287 | 306 | 408.2493 m. | 1.1448 | 0.9379 |

roadmap complexity and beacons received, obtained in the previous phases. Next subsections present the different phases of our mechanism.

### 3.3.1 Phase 1: Features of the Cities Studied

An important issue to our vehicular density estimation approach is to obtain the different features of each roadmap (e.g., the number of streets, the number of junctions, the average distance of segments, and the number of lanes per street).

The roadmaps used to achieve the density estimation were selected in order to have different profile scenarios (*i.e.*, with different topology characteristics). We studied eight different cities (San Francisco, Valencia, Rome, Rio de Janeiro, Sydney, Amsterdam, Madrid, and Los Angeles). Figure 3.1 shows the topologies of the cities studied. Although some differences can be visually perceived, a more thorough analysis must be performed to determine and classify the topology of each map.

Table 3.1 shows the main features of each map of the cities under study (*i.e.*, the number of streets according to the RAV radio propagation model [MFT+13], where the visibility between vehicles is taken into consideration when identifying the different streets, the number of junctions, the average distance of segments, and the number of lanes per street.

We consider that the parameters that better correlate with the complexity of the roadmap are the number of streets and the number of junctions. Hence, we also added a column labeled as *SJ Ratio*, which represents the result of dividing the number of streets between the number of junctions. As shown, the first 5 cities (Rome, Rio, Valencia, Sydney, and Amsterdam) present an SJ ratio greater than 1, which indicates that they have a complex topology, while the rest of the cities (Madrid, San Francisco, and Los Angeles) present a lower SJ value, which indicates that they have a simple topology. Note that, although Rio de Janeiro has a relatively small number of streets and junctions, it has a complex topology since its SJ Ratio is greater than 1.

### 3.3.2 Phase 2: Counting the Number of Beacons Received

After performing the topological analysis of the studied maps, we need to obtain the number of beacons received by each vehicle during a certain period of time.

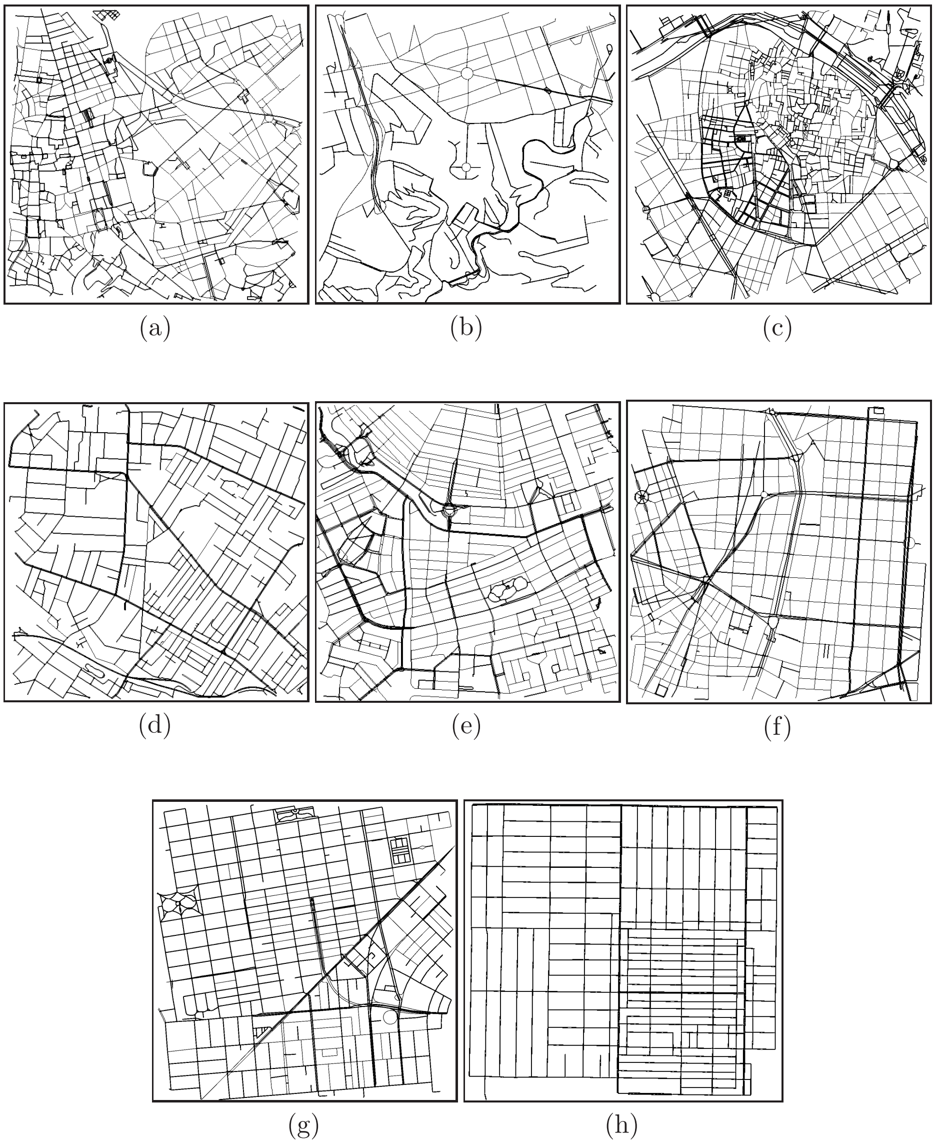



Figure 3.1: Scenarios used in our simulations. Fragments of the cities of: (a) Rome (Italy), (b) Rio de Janeiro (Brazil), (c) Valencia (Spain), (d) Sydney (Australia), (e) Amsterdam (Netherlands), (f) Madrid (Spain), (g) San Francisco (USA), and (h) Los Angeles (USA).

This period is very important, since it will affect the number of beacons received, and the accuracy of the vehicular density estimation.

According to the results obtained in Section 3.3.3.1, in our scheme, we obtain the number of beacons received during 30 seconds. We consider that each vehicle sends one beacon per second, and that these messages, unlike warning messages, are not disseminated by the rest of the vehicles. These considerations can be found in many previous Vehicular Network studies, so they could be considered quite realistic.

Simulation results presented in this chapter were obtained using the the simulation environment presented in Section 2.4.

In particular, we tested our model by evaluating the performance of a Warning Message Dissemination mechanism, where each vehicle periodically broadcasts information about itself, or about an abnormal situation (icy roads, traffic jam, *etc.*). In order to mitigate the broadcast storm problem [TNCS02], our simulations use the enhanced Message Dissemination based on Roadmaps (eMDR) scheme [FGM$^+$12b]. The eMDR scheme only allows forwarding messages when the distance between sender and receiver is greater than a threshold, or in situations where the receiver is the closest vehicle to a junction, and rebroadcasting could allow the message to reach vehicles in adjacent streets.

Table 3.2 shows the parameters used for the simulations. All the results represent an average of over 50 repetitions with different scenarios (maximum error of 10% with a degree of confidence of 90%), and each simulation run lasted for 180 seconds.

Figure 3.1 shows the map layouts of the different cities studied, and Figure 3.2 shows the results obtained. We also included two lines that depict the average values for each profile category (*i.e.*, simple and complex average). As shown, two different groups can be distinguished: (i) the complex maps, which are located in the left part of the figure, and (ii) the simple maps, which are located in the right part of the figure.

As expected, complex roadmaps present a number of beacons received lower than simple roadmaps for a similar vehicular density. In addition, we found that the simpler cities present a high similitude in terms of results, being more difficult to estimate the vehicular density in complex cities compared with simple cities. Figure 3.2 demonstrates that the vehicular density depends not only on the number of beacons received, but also on the characteristics of the roadmap where the vehicles are located. Therefore, the characteristics of the roadmap will be very useful in order to accurately estimate the vehicular density in a given scenario. According to data shown in Table 3.1, the SJ ratio can be used to characterize the different maps.

Table 3.3 shows the average percentage difference with respect to the mean value. From the obtained results we observe that the cities that show a better fit for the average results are Valencia (in the complex topology group) and San Francisco (in the simple topology group). Hence, these cities could be used as reference to obtain representative results when simulating Vehicular Networks.

### 3.3.3 Phase 3: Density Estimation Function

After observing the direct relationship between the topology of the maps, the number of beacons received, and the density of vehicles, we proceed to obtain a

Table 3.2: Parameters used for the simulations.

| **Parameter** | **Value** |
|---|---|
| roadmaps | Rome, Rio de Janeiro, Valencia, Sydney, Amsterdam, Madrid, San Francisco, and Los Angeles |
| number of vehicles | $[100, 200, 300...1000]$ |
| number of collided vehicles | 3 |
| roadmap size | $2000\ m \times 2000\ m$ |
| warning message size | $256B$ |
| beacon message size | $512B$ |
| warning messages priority | $AC3$ |
| beacon priority | $AC1$ |
| interval between messages | 1 second |
| MAC/PHY | 802.11p |
| radio propagation model | $RAV$ [MFT+13] |
| mobility model | $Krauss$ [KWG97] |
| channel bandwidth | $6\ Mbps$ |
| max. transmission range | $400\ m$ |

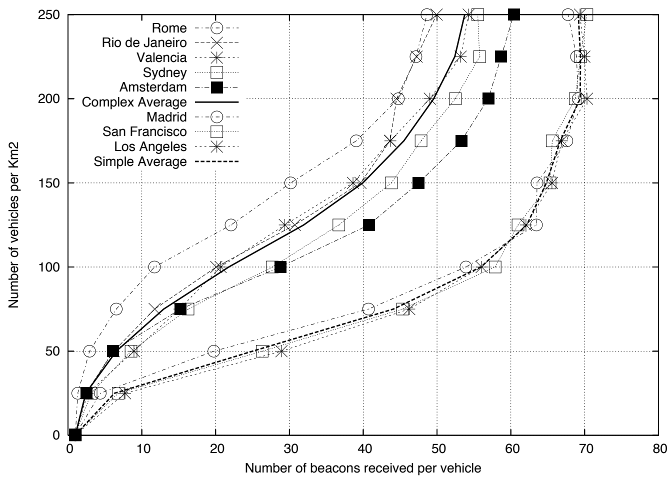



Figure 3.2: Number of beacons received when varying the vehicular density.

function to estimate, with the minimum possible error, each of the curves shown in Figure 3.2.

To propose a method able to accurately estimate the density of vehicles, based on the number of beacons received and the roadmap topology, we made a total of 4,000 experiments. These experiments involved the simulation of controlled scenarios (*i.e.*, scenarios where the actual density is known). According to the results obtained, we propose a density estimation function capable of estimating the vehicular density in every urban environment, at any instant of time.

Table 3.3: Average percentage difference with respect to the mean value.

| City | Percentage Difference |
|---|---|
| Rome | 29.49% |
| Rio De Janeiro | 5.85% |
| **Valencia** | **4.56%** |
| Sydney | 15.82% |
| Amsterdam | 14.96% |
| Madrid | 6.44% |
| **San Francisco** | **1.74%** |
| Los Angeles | 4.70% |

Table 3.4: Proposed equation coefficients.

| Coeff. | Value |
|---|---|
| a | -1.1138191190298828E+03 |
| b | -1.0800433554686800E+01 |
| c | 3.1832185406821718E+03 |
| d | -4.0336415134812398E-01 |
| f | -3.0203454502011946E+03 |
| g | 2.8542014049626700E-03 |
| h | 9.5199929660347175E+02 |
| i | 3.5319225007012626E+01 |
| j | 1.6230525995036607E-01 |
| k | -1.6615888771467137E+01 |

In order to obtain the best approach, we have tested some different functions (exponential, logarithmic, *etc.*). To this purpose, we performed a regression analysis [Zun12] that allowed us to find the polynomial equation offering the best fit to the data obtained through simulation. Equation 3.1 shows the density estimation function, which is able to estimate the number of vehicles per km$^2$ in urban scenarios, according to the number of beacons received, and the SJ ratio (*i.e.*, streets/junctions).

$$f(x,y) = a + bx + cy + dx^2 + fy^2 + gx^3 + hy^3 + ixy + jx^2y + kxy^2 \tag{3.1}$$

In this equation, $x$ is the number of beacons received by each vehicle, and $y$ is the SJ ratio obtained from the roadmap. The values of the polynomial coefficients $(a, b, c, d, f, g, h, i, j,\ and\ k)$ are listed in Table 3.4, and Figure 3.3 shows the 3-dimensional representation of the proposed equation.

Equation 3.2 presents the best non-polynomial approach we obtained. However, in terms of accuracy, the sum of squared absolute error of this function is of 3.8618E+04, while the polynomial function presents a lower value (6.3321E+03). Thus, we considered to use the first equation in our approach.

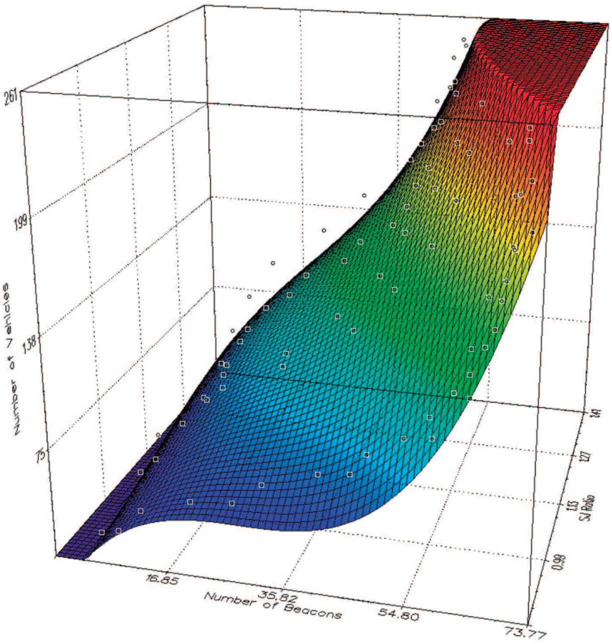



Figure 3.3: 3D representation of our density estimation function.

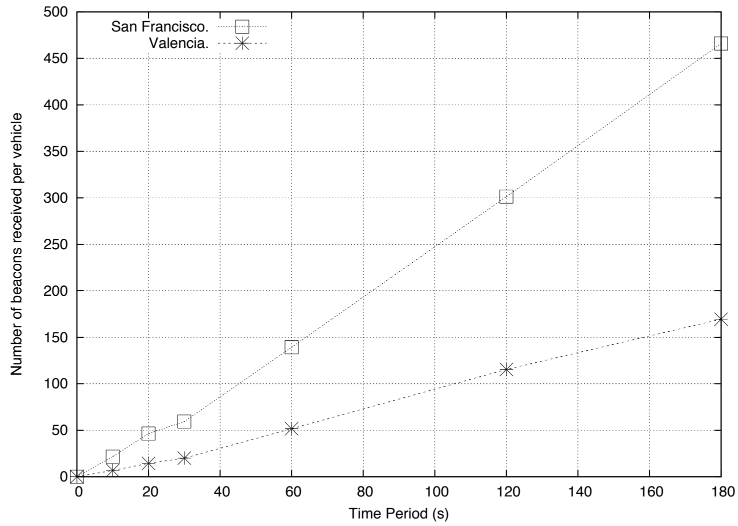
$$f(x,y) = \frac{16a \cdot exp(-(\frac{x-b}{c}) - (\frac{y-d}{f}))}{(1 + exp(-(\frac{x-b}{c})))^2 \cdot (1 + exp(-(\frac{y-d}{f})))^2} \tag{3.2}$$

#### 3.3.3.1 Time Period Analysis

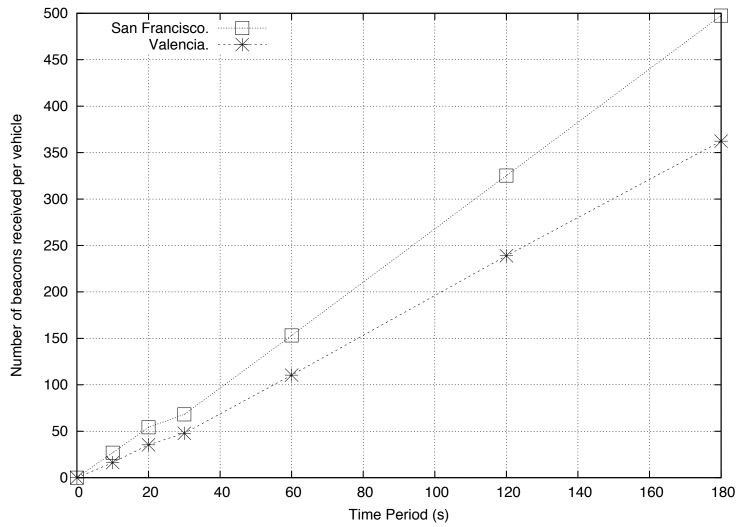
As mentioned before, our proposal is based on two key factors: (i) the roadmap topology, which is provided by the in-vehicle GPS systems, and (ii) the number of beacons received at a given period of time. Hence, in a vehicular density estimation system, it is very important to decide how much time is dedicated to gather important and necessary data in order to better estimate the density of vehicles at any given time.

In order to determine the optimal period of time that should be considered to estimate the density in vehicular environments, thereby enhancing the performance of the density estimation process, we made a total of 600 experiments including six different time periods (*i.e.*, $10, 20, 30, 60, 120, 180$ seconds), and using the maps of Valencia and San Francisco.

Figure 3.4 shows the number of beacons received by each vehicle when simulating 100 and 200 vehicles$\cdot$km$^{-2}$, respectively. As shown, complex maps are more affected by vehicular density variations, since messages encounter more difficulties to be propagated in these kinds of maps, especially in lower density scenarios.




(a)




(b)

Figure 3.4: Number of beacons received per vehicle when varying the time period and the city roadmap when simulating: (a) 100 vehicles·km$^{-2}$, and (b) 200 vehicles·km$^{-2}$.

Table 3.5: Absolute error when varying the time period.

| **Time (s)** | **Median** | **Variance** |
|---|---|---|
| 10 | -5.073593E-03 | 1.483517E-03 |
| 20 | -1.515514E-03 | 1.048494E-03 |
| **30** | **-2.972316E-03** | **7.569214E-04** |
| 60 | 2.377369E-01 | 1.241401E+03 |
| 120 | 7.621857E+00 | 1.548736E+03 |
| 180 | 5.128145E+00 | 1.492756E+03 |

Regarding the optimal time period, since results are quite linear, a larger time period seems to be the best option; notice that this solution requires fewer calculations, thereby reducing the overhead. However, a more thorough analysis should be made to determine the optimal time period required to gather the number of beacons received.

To find the best period, we also analyzed the error committed when using different time periods. Specifically, we fitted the function coefficients to each period, and then calculated the absolute error committed.

Table 3.5 shows the median and the variance of the absolute error for each period analyzed. As shown, lower periods obtain more accurate results. In fact, when the time period exceeds 30 seconds, the error increases by two orders of magnitude. Having discarded larger periods, we consider that the best period to gather data is of 30 seconds, since the absolute error offers a lower variance.

### 3.3.4 The Concept of Street

Our vehicular density estimation approach uses three different parameters: (i) the number of beacons received, (ii) the number of junctions, and (iii) the number of streets. As for the number of junctions, it is only necessary to count the junctions between different street segments. However, regarding the number of streets, we realized that different alternatives could be selected to obtain the number of streets in a given roadmap.

Basically, the different alternatives are: (i) the number of streets obtained in SUMO [KR12], where each segment between two junctions is considered a street, (ii) the number of streets obtained in [Ope12] (OSM), where each street has a different “name”, and (iii) the number of streets according to the RAV radio propagation model [MFT+13], where the visibility between vehicles is taken into consideration when identifying the different streets.

Figure 3.5 shows a small portion of New York City to depict the different criteria when counting the number of streets. For example, Thames Street is considered only one street in OSM, whereas the SUMO and RAV models consider that there are two different streets instead. However, if we observe Cedar Street, the RAV visibility model and the OSM approaches consider a single street (as expected), whereas it is represented by three different streets according to SUMO, since it has three different segments. Finally, according to both the OSM and SUMO approaches, Trinity Place and Church Street are represented as two different streets,


Figure 3.5: Different criteria when counting the number of streets.

Table 3.6: Number of streets obtained depending on the criterion used.

| City | SUMO | OSM | RAV |
|---|---|---|---|
| Rome | 2780 | 1484 | 1655 |
| Rio de Janeiro | 758 | 377 | 542 |
| Amsterdam | 3022 | 796 | 1494 |
| Madrid | 1387 | 1029 | 628 |

Table 3.7: Density estimation error.

| Error | Absolute | Relative |
|---|---|---|
| Minimum | -2.612027E+01 | -2.284800E-01 |
| Maximum | 2.169529E+01 | 5.713108E-01 |
| Mean | -3.176197E-10 | 1.023340E-02 |
| Std. Error of Mean | 1.360303E+00 | 1.714082E-02 |
| Median | 1.698901E-01 | -1.359121E-03 |

whereas the RAV model considers that only one street exists.

Table 3.6 shows the values obtained when counting the number of streets of some of the cities studied, according to each criterion (*i.e.*, SUMO, OSM, or RAV). As shown, the differences between these approaches are significant, meaning that it is important to decide which one to use in order to obtain accurate and realistic results. After some experiments, we realized that the third approach better correlates with the real features of cities, since the other two present some drawbacks: they are not accurate enough, or they present some errors (e.g., SUMO always considers segments between junctions as streets, and using street names to estimate the communication between the vehicles may result in inaccurate estimations). So, we choose the RAV model to count the number of streets in our vehicular density estimation mechanism.

## 3.4 Validation of Our Proposal

To determine the accuracy of our proposal, we proceed to measure the estimated error. Figure 3.6 shows the difference between the average values for all the cities studied, and the values obtained by our function. As shown, we achieve a good fit for the average values obtained in the simulations. In addition, Table 3.7 shows the different types of errors calculated when comparing our density estimation function with the values actually obtained. Note that the average relative error is only 1.02%.

Finally, Figure 3.7 shows the absolute error histogram. As shown, results are mainly concentrated around zero, which confirms that our proposal is consistent with the expected results, and that the density estimation is accurate enough.

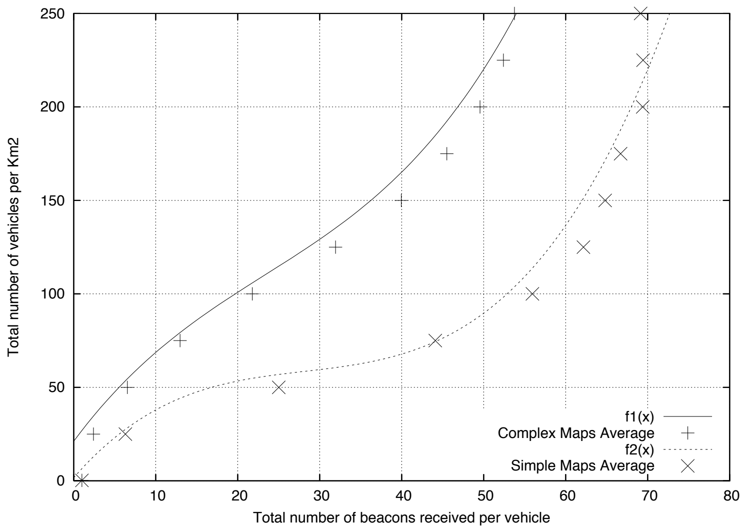



Figure 3.6: Comparison between simulated and estimated average results.

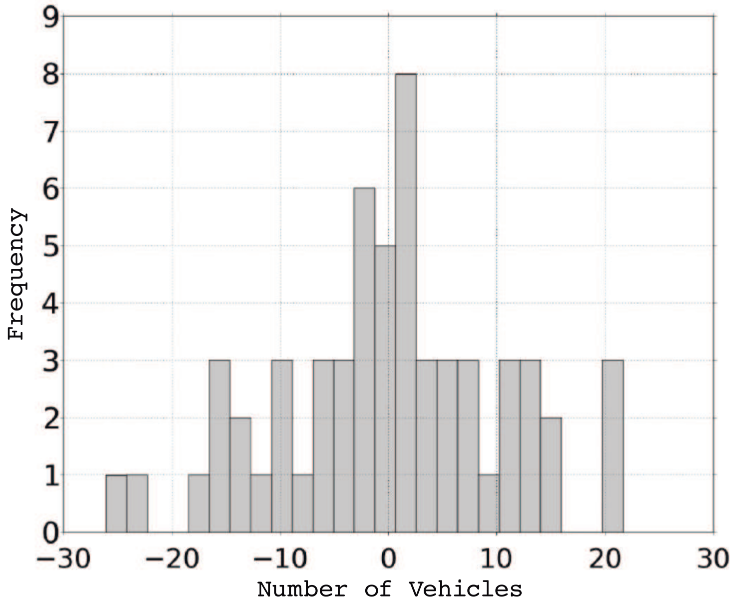



Figure 3.7: Absolute error histogram.

Table 3.8: Beacons-only functions' coefficients.

| Coefficient | Quadratic | Cubic | Quartic | Preece–Baines |
|---|---|---|---|---|
| a | 1.829427E+01 | 2.276843E+01 | 3.904724E+01 | 1.908715E+02 |
| b | 4.136735E+00 | 3.294135E+00 | -1.384712E+00 | 1.632780E+02 |
| c | -2.150912E-02 | 7.028936E-03 | 2.975870E-01 | 2.567304E-02 |
| d | - | -2.555843E-04 | -6.471301E-03 | 4.405584E+01 |
| f | - | - | 4.274130E-05 | 6.866641E-01 |

## 3.5 Comparing Our Proposal with a Beacons-Based Density Estimation Approach

As previously mentioned, other vehicular density estimation proposals rely on the use of infrastructure elements to estimate the vehicle density (e.g., [TKK12], and [TC07]). On the contrary, the proposals based on V2V communications do not require the deployment of any infrastructure nodes, but they usually take into account just the number of beacons received (e.g., [MBML11], and [SCB11]), while omitting any data related to the map topology where the vehicles are located at.

In order to assess the importance of the topology, we compared our proposal with a beacon-based approach, where the vehicular density is estimated by only using the number of beacons received. To make a fair comparison, we followed the same methodology in both approaches.

We tested four different density estimation functions that are only based on the number of beacons received, trying to obtain the lowest sum for the squared absolute error. Specifically, we have tested three different polynomial functions (*i.e.*, quadratic, cubic, and quartic), and a non-polynomial function (based on the Preece–Baines Growth function). Equations 3.3–3.6 show these functions, and Table 3.8 shows their coefficients.

$$f(x) = a + bx + cx^2 \tag{3.3}$$

$$f(x) = a + bx + cx^2 + dx^3 \tag{3.4}$$

$$f(x) = a + bx + cx^2 + dx^3 + fx^4 \tag{3.5}$$

$$f(x) = \frac{a - 2 \cdot (a - b)}{(exp(c \cdot (x - d)) + exp(f \cdot (x - d)))} \tag{3.6}$$

Table 3.9 shows the square absolute error sum for each of the functions tested. As shown, our SJ Ratio function yields more accurate results, presenting the lower sum for the square absolute error (approximately 6.332E+03, two orders of magnitude lower than the others), and it only commits an error of 8.8967 vehicles, whereas the rest of the functions that only account for the number of beacons commit an error ranging from 40.5017 to 41.5684 vehicles, depending on the selected function.

Table 3.9: Comparison between our SJ Ratio and the Beacon-based density estimation approaches.

| **Fitted function** | **Sum of square absolute error** | **Vehicles error** |
|---|---|---|
| Beacons-only Quadratic | 1.382345E+05 | 41.5684 |
| Beacons-only Cubic | 1.379941E+05 | 41.5322 |
| Beacons-only Quartic | 1.360938E+05 | 41.2453 |
| Beacons-only Preece-Baines G. | 1.312314E+05 | 40.5017 |
| **SJR Full Cubic** | **6.332155E+03** | **8.8967** |

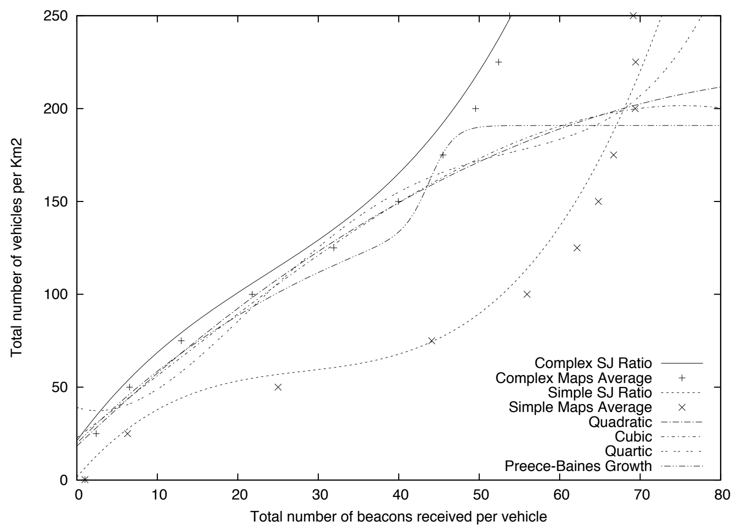



Figure 3.8: Graphical comparison between simulated and estimated results for each function.

Figure 3.8 shows how our approach fits well with both the Complex and Simple Maps, since it adjusts the estimation made, accounting not only for the number of beacons received, but also for the features of the maps where the vehicles are located. On the contrary, those approaches that only take into account the number of beacons received correctly estimate the density of vehicles in complex maps, specifically in low and mid-density scenarios (less than 150 vehicles$\cdot$km$^{-2}$). However, they underestimate the number of vehicles in high density environments, and, most importantly, they overestimate the density of vehicles in Simple maps.

Therefore, the advantages of using our vehicular density estimation proposal are clear in terms of accuracy. Our approach requires using GPS and digital maps, but these requirements are currently fulfilled by most of the vehicles in many countries.

## 3.6 Summary

This chapter proposes a method that allows vehicles to estimate the vehicular density in their neighborhood at any given time by using Vehicular Networks. Our proposal allows scientists to improve their proposals, or propose new solutions, based on our findings.

Unlike existing proposals, our vehicular density estimation mechanism accounts not only for the number of beacons received per vehicle, but also for the map topology in the region where the vehicles are located. Our method consists of three phases: (i) we first analyze the features of different cities, (ii) the vehicles obtain the number of beacons received, and (iii) each vehicle estimates the vehicular density in its neighborhood by applying an equation that requires as input parameters the values in terms of roadmap complexity and beacons received.

Results show that our proposal allows estimating the vehicular density for any given city with a high accuracy. We also demonstrated that the characteristics of the roadmap are very useful in order to accurately estimate the vehicular density in a given scenario.

# Chapter 4

# RTAD: Real-Time Adaptive Dissemination System

Efficient message dissemination is of utmost importance to propel the development of useful services and applications in Vehicular ad hoc Networks (VANETs). In this chapter, we propose a novel adaptive system that allows each vehicle to automatically adopt the optimal dissemination scheme in order to fit the warning message delivery policy to each specific situation. Our mechanism uses as input parameters the vehicular density and the topological characteristics of the environment where the vehicles are located, in order to decide which dissemination scheme to use. We compare our proposal with respect to two static dissemination schemes (eMDR and NJL), and three adaptive dissemination systems (UV-CAST, FDPD, and DV-CAST). Simulation results demonstrate that our approach significantly improves upon these solutions, being able to support more efficient warning message dissemination in all situations ranging from complex maps to simple scenarios with different densities. In particular, RTAD improves existing approaches in terms of percentage of vehicles informed, while significantly reducing the number of messages sent, thus mitigating broadcast storms.

## 4.1 Introduction

The specific characteristics of VANETs favor the development of attractive and challenging services and applications, including road safety [GFAB13], traffic flow management [SMGMRR10], road status monitoring [LSL+08], environmental protection [NKJ+12], and mobile infotainment [SDFCB12]. We focus on traffic safety and efficient warning message dissemination, where the main goal is to reduce the latency and to increase the accuracy of the information received by nearby vehicles when a dangerous situation occurs [ZZG+08].

When a vehicle detects an abnormal situation such as an accident or slippery road it rapidly starts to notify the anomaly to nearby vehicles in order to spread the alert information in a short period of time [KCR13]. Thus, broadcasting warning messages can be useful to alert nearby vehicles. However, this dissemination is strongly affected by: (i) the signal attenuation due to the distance between the sender and receiver (especially in low vehicular density areas), (ii) the effect of obstacles in signal transmission (very usual in urban areas, e.g., due to buildings), and (iii) a reduced message delivery effectiveness due to serious redundancy, contention, and massive packet collisions provoked by simultaneous forwarding, usually known as broadcast storm (prone to occur in highly congested areas) [TNCS02]. Therefore, knowing the density of vehicles and the characteristics of the area where the vehicles are moving (e.g., in terms of topological complexity) can offer better opportunities for message delivery.

We consider that new adaptive proposals for warning message dissemination in urban environments are needed, offering efficient broadcasting techniques around the affected area, taking into account the current vehicular density, as well as the topology of the scenario where vehicles are located. This can be beneficial in order to increase the efficiency of the warning message dissemination process, and also to reduce broadcast storm related problems.

In this chapter we propose RTAD, a real-time adaptive dissemination system that allows each vehicle to automatically adopt the optimal dissemination scheme to adapt the warning message delivery policy to each specific situation. Our mechanism uses as input parameters the vehicular density and the topological characteristics of the environment where the vehicles are located, using them to decide which dissemination scheme to use. The main goal is to maximize the message delivery effectiveness while generating a reduced number of messages and, thus, avoiding or mitigating broadcast storms. In addition, we also propose the Nearest Junction Located (NJL), our novel warning message dissemination scheme specially designed for being used in highly congested urban areas due to the lack of schemes with this specific purpose.

In order to assess RTAD's performance, we tested it under four different scenarios: two of them previously used to calibrate the algorithm (Amsterdam and Los Angeles), and two new scenarios (Sydney and Santiago de Chile) characterized by larger map areas, as well as having one (Sydney) or two (Santiago de Chile) different downtown areas. Finally, we have included a comparison between our proposal and two static broadcast schemes (eMDR and NJL), as well as three adaptive systems (UV-CAST, FPDP and DV-CAST).

The chapter is organized as follows: in Section 4.2 we review previous works closely related to our proposal, highlighting the main similarities and differences. In Section 4.3 we present the simulation environment used to validate our proposal. In Section 4.4 we make a preliminary analysis of different broadcast schemes, and we present the optimal broadcast selection algorithm proposed. Section 4.5 introduces RTAD, our real-time adaptive warning dissemination system. Section 4.6 presents and discusses the obtained results. Finally, Section 4.7 concludes this chapter.

## 4.2 Related Work

In the networking literature we can find several works that present adaptive mechanisms specially designed to enhance message dissemination in vehicular communications. In this section we present some of the most representative works.

Ros et al. [RRS09] presented a broadcast protocol suitable for a wide range of vehicular scenarios and traffic conditions. The protocol employs local position information acquired via periodic beacon messages. Identifiers of circulated broadcast messages are added to beacons as piggybacked acknowledgments. When waiting timeout expires, vehicle retransmits if it has at least one neighbor which did not acknowledge circulated message with the last beacon, and sets a new waiting period. Despite its simplicity, the protocol provides high reliability and efficiency by means of a simulation-based performance evaluation.

Monteiro et al. [MSVT13] simulated highway and urban VANET scenarios of different sizes and vehicle densities. They studied parameters such as the node degree distribution, the clustering coefficient and the average shortest path length, then they showed how to use this information to improve existing VANET protocols. As an illustrative example, it is shown that, by adding new mechanisms that make use of this information, the overhead of the urban vehicular broadcasting (UV-CAST) protocol could be reduced substantially with no significant performance degradation.

Xuewen et al. [XwWSmHb10] proposed the Transmission Range Adaptive Broadcast (TRAB), a broadcast algorithm for VANETs. By considering the transmission ranges of vehicles together with the inter-vehicle distances, TRAB calculates the waiting time to select the relay vehicles in accordance with the additional coverage area of adjacent vehicles to ensure that fewer relay vehicles will be used to forward the warning messages. However, this scheme is designed to obtain an efficient propagation of warning messages in highway scenarios alone, making it unsuitable for scenarios with complex topologies where the dissemination of warning messages in all directions surrounding the critical area would be required.

Slavik et al. [SMA12] proposed the Rate-Adaptive Broadcast (RAB) protocol for information dissemination in VANETs. RAB adapts to the network conditions, although it does not require any knowledge of the network topology. By assuming a VANET dissemination application with fixed periodic updates, RAB is able to use a decision threshold control algorithm based on the message rate. If the new message rate dips below its long-run average, the decision threshold is adjusted to improve message propagation. Otherwise, RAB adjusts the decision threshold to keep the duplicate message rate within an efficient range. Thus, RAB jointly optimizes the broadcast message delivery rate and the bandwidth consumption. Unlike the TRAB scheme, the use of RAB is not restricted to highways; nevertheless, the roadmap layout is not used to select the vehicles to forward the messages. Instead, the scenario is modeled like a free space environment where vehicles only try to send messages as far away as possible, without accounting for the different blind areas that buildings may produce during the dissemination process.

Sommer et al. [STD11] proposed the Adaptive Traffic Beacon (ATB), a fully distributed message dissemination protocol which uses adaptive beaconing based on two key metrics: message utility and channel quality. Authors showed that adaptive beaconing leads to a much broader dissemination of messages (in terms of penetration rate) than flooding-based approaches, although at a slower rate. The main objective of ATB is to exchange information in knowledge bases by sending beacons as frequently as possible, while maintaining a congestion-free wireless channel. However, their proposal cannot be applied in time-critical safety applications where the quick dissemination of warning messages is crucial. Additionally, authors only tested their proposal in a roadmap portion of Ingolstadt, Germany.

Ke et al. [KWdJZDt11] proposed the Adaptive Connectivity Data Dissemination Scheme (ACDDS), a data dissemination strategy where the vehicles calculate the network connectivity in their neighborhood by using the distributed vehicular density perception algorithm. A hop limit function is established on the basis of the Euclidean distance and the vehicular density between the vehicles and the hotspot. Simulation experiments show that the delivery ratio and the delay values for the proposed scheme are similar to the epidemic routing protocol, while reducing the number of message copies by 37.5%. To validate their proposal, authors used real mobility traces obtained from 479 taxis in the San Francisco area. However, they did not use mobility traces for other types of vehicles, the density of vehicles was really low, and they did not account for the presence of obstacles in wireless signal propagation. These assumptions could lead to unrepresentative results.

Schwartz et al. [SOS+12] proposed a data dissemination protocol for VANETs that distributes data utility fairly over vehicles while adaptively controlling the network load. The protocol relies only on local knowledge to achieve fairness using concepts of Nash Bargaining from game theory. Simulation results show that their algorithm presents a higher fairness index, while maintaining a high level of bandwidth utilization efficiency. In addition, the rate of transmissions is adaptively controlled as new information about the environment is collected. However, the vehicular density of the scenarios where their proposal was tested was very low (i.e., only 20 vehicles/km$^2$). Additionally, it is not clearly explained if their simulations accounted for the effect of obstacles in wireless signal propagation, and the benefits of their proposal in terms of vehicles informed.

Overall, we find that existing adaptive dissemination techniques for VANETs usually consider features related to vehicles in the scenario, such as their density, speed, and location, to adapt the performance of the dissemination process. However, most of the works in the literature are designed for highway scenarios where messages are only propagated in one direction, or focused on end-to-end routing. Additionally, most of them do not account for the effect of buildings and other obstacles during the dissemination of messages, which may lead to wrong conclusions. Hence, these approaches are not useful when attempting to warn the highest possible number of vehicles about dangerous situations in realistic vehicular environments, especially in urban environments.

## 4.3 Simulation Environment

Simulation results presented in this chapter were obtained using the the simulation environment presented in Section 2.4.

The roadmaps used in the simulations were selected in order to have different profile scenarios (i.e., with different topology characteristics). Figure 4.1 and Table 4.1 show the topology and the main features of the cities simulated, respectively.


Figure 4.1: Scenarios selected in our simulations. Fragments of the cities of: (a) Rome (Italy), (b) Valencia (Spain), (c) Sydney (Australia), (d) Amsterdam (Netherlands), (e) Los Angeles (USA), (f) San Francisco (USA), and (g) Madrid (Spain).

Table 4.1: Map features.

| Map | Streets | Junctions | SJ Ratio |
|---|---|---|---|
| Rome | 1655 | 1193 | 1.387 |
| Valencia | 2829 | 2233 | 1.267 |
| Sydney | 872 | 814 | 1.071 |
| Amsterdam | 1494 | 1449 | 1.031 |
| Los Angeles | 287 | 306 | 0.938 |
| San Francisco | 725 | 818 | 0.886 |
| Madrid | 628 | 715 | 0.878 |

Note that we added a column labeled as *SJ Ratio*, which represents the result of dividing the number of streets between the number of junctions. As shown, the first four cities (Rome, Valencia, Sydney, and Amsterdam) present an SJ ratio greater than 1, which indicates that they have a complex topology, while the rest of the cities (Los Angeles, San Francisco, and Madrid) present a lower SJ value, which indicates that they have a simple topology.

We are interested in the following performance metrics previously presented in Section 2.4: (i) percentage of informed vehicles, and (ii) number of messages received per vehicle.

In this work we performed more than 28,000 experiments, since we made 50 repetitions for each scenario while also varying the city roadmaps, the density of vehicles, and the broadcast scheme used. According to our previous work, we included the results obtained for San Francisco and Valencia since, the simulation results obtained in these roadmaps are closer to the average ones. Table 4.2 shows the parameters used for the simulations.

## 4.4 RTAD: Analysis of the Optimal Broadcast Scheme

One of the main characteristics of VANETs is the great variability of the conditions affecting each vehicle. Thus, broadcasting decisions taken should not remain immovable. Instead, the dissemination system should dynamically adapt its broadcasting policy to the specific characteristics and situations, thereby improving the whole dissemination process. In this work we propose RTAD, a real-time adaptive dissemination system specially designed for VANETs, in which each vehicle individually adopts a specific dissemination scheme according to each situation. In our proposed system, each vehicle is able to obtain and analyze the characteristics of the environment, thereby choosing the optimal diffusion policy in each situation. To select the optimal broadcast scheme for a specific scenario, RTAD accounts for two different performance metrics (i.e., the vehicle density and the roadmap topology), that allow it to determine which dissemination scheme to use at any time.

In order to determine which are the optimal broadcast schemes that our RTAD can use for each particular scenario, in this section we first review the most relevant

Table 4.2: Parameter settings in the simulations.

| **Parameter** | **Value** |
|---|---|
| roadmaps | Rome, Valencia, Sydney, Amsterdam, Los Angeles, San Francisco, Madrid |
| number of vehicles per km$^2$ | $[25, 50, 100, 150, 200, and\ 250]$ |
| roadmap size | $2000m \times 2000m$ |
| warning message size | $256B$ |
| beacon message size | $512B$ |
| warning messages priority | $AC3$ |
| beacon priority | $AC1$ |
| interval between messages | 1 second |
| MAC/PHY | 802.11p |
| radio propagation model | $RAV$ [MFT+13] |
| mobility model | $Krauss$ [KWG97] |
| channel bandwidth | $6Mbps$ |
| max. transmission range | $400m$ |
| $d_{min}$ (used in distance-based, eSBR, and eMDR) | $200m$ |
| simulation run | $120s$ |

ones; then we present in detail the main metrics we use to measure the broadcast schemes' goodness, and finally, we introduce the optimal broadcast selection algorithm.

### 4.4.1 Broadcast Schemes Used

So far, several authors have proposed different dissemination schemes to mitigate broadcast storms [TNCS02, WTP+07, SP08, BCSZ10, SM10]. However, all of these schemes consider free space environments where no blocking obstacles are considered at all. They have not addressed the impact of buildings and other urban obstacles on the wireless signal propagation in realistic urban scenarios. The consequences derived from those incomplete analyses can be observed when their performance is tested in realistic urban topologies, showing that they are unable to choose suitable relaying vehicles, or proving to be too restrictive to achieve an efficient dissemination [MFC+10]. Some of the most representative broadcast schemes are briefly presented below.

- The *Counter-based scheme* [TNCS02]. Initially proposed for Mobile Ad Hoc Networks (MANETs), this scheme aims at mitigating broadcast storms by using a threshold $C$ and a counter $c$ to keep track of the number of times a broadcast message is received. Whenever $c \geq C$, rebroadcast is inhibited.

- The *Distance-based scheme* [TNCS02]. This scheme accounts for the relative distance $d$ between vehicles to decide whether to rebroadcast or not. When the distance $d$ between two vehicles is short, the additional coverage (AC) area of the new rebroadcast is lower, and so rebroadcasting the warning message is not recommended. Forwarding is only beneficial when the additional coverage is nearly maximum.

- The *enhanced Street Broadcast Reduction* (eSBR) [MFC+10]. This scheme is specially designed to be used in VANETs, taking advantage of the information provided by maps and built-in positioning systems, such as the GPS. Vehicles are only allowed to rebroadcast messages if they are located far from their source ($> d_{min}$), or if the vehicles are located in different streets, giving access to new areas of the scenario. The eMDR scheme uses information about the roadmap to avoid blind areas due the presence of urban structures blocking the radio signal.

- The *enhanced Message Dissemination for Roadmaps* (eMDR) [FGM+12b]. As an improvement to the eSBR scheme, eMDR increases the efficiency of the system by avoiding to forward the same message multiple times if nearby vehicles are located in different streets. Specifically, vehicles use the information about the junctions of the roadmap, and only the vehicle closest to the geographic center of the junction, according to the geopositioning system, is allowed to forward the messages received. This strategy aims at reducing the number of broadcasted messages while maintaining a high percentage of vehicles informed.

- The eMDR and eSBR schemes proved to be especially effective in sparse urban environments. However, the number of messages produced may become excessive in scenarios with a high vehicle density. To cope with this deficiency, in this chapter we also propose a novel dissemination scheme called *Nearest Junction Located* (NJL) that is completely based on the topology of the roadmap, allowing vehicles to rebroadcast a message only if they are the nearest vehicle to the geographical coordinates of any junction obtained from the integrated maps. This scheme follows a procedure similar to the eMDR algorithm, although ignoring the distance between sender and receiver; thus, it only focuses on the location of the receiving vehicle. As shown in the two next subsections, although the performance of this algorithm is not optimal in sparse environments, it performs quite well in high-density scenarios where the dominant factor to improve the dissemination process is the position of the vehicles, achieving results similar to those obtained by the eMDR and eSBR schemes, while requiring only a fraction of the overall number of messages.

To better understand the operation of the eSBR, eMDR, and NJL algorithms, we provide a formal definition of these schemes using set theory. In the mentioned formulation, the following notation is used:

- $\mathbb{V}$: set of vehicles present in the scenario.
- $\mathbb{N}_i$: set of neighbor vehicles of vehicle $v_i \in \mathbb{V}$.
- $\mathbb{M}$: set of warning messages disseminated by vehicles.

- $\mathbb{J}$: set of junctions of the road layout.

The definition of the algorithms requires some basic functions to express events and relationships between the components of the scenario. Specifically, the following functions are required:

- $recv(v_r, v_s, m, t)$: vehicle $v_r$ receives a warning message $m$ from vehicle $v_s$ at time $t$.

- $dist(e_1, e_2)$: Euclidean distance between elements $e_1$ and $e_2$, i.e.:

$$dist(e_1, e_2) = \sqrt{(e_1.x - e_2.x)^2 + (e_1.y - e_2.y)^2} \tag{4.1}$$

- $rebroadcast(v, m, t)$: vehicle $v$ broadcasts a warning message $m$ at time $t$.

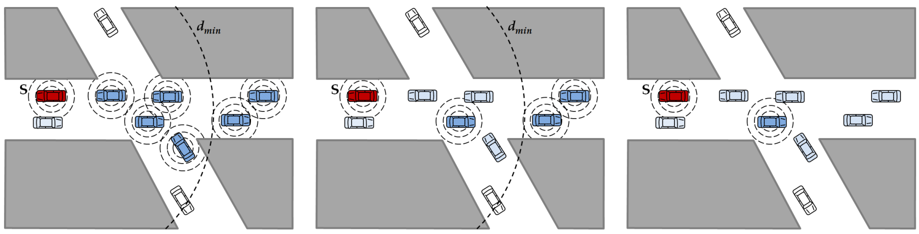
Equation 4.2 shows the formulation of the eSBR algorithm. As can be observed, after receiving a warning message from a vehicle $v_s$, each vehicle $v_r$ rebroadcasts the message if the distance between the sender vehicle $v_s$ and the receiver vehicle $v_r$ is greater than a minimum rebroadcast distance $d_{min}$, set in our simulations to 200 $m$; or if $v_r$ is located near a junction $j$, giving access to new streets possibly blocked by the effect of buildings on radio signal. A threshold $th_j$ of 20 $m$ is used to determine whether the vehicle is located near a junction in the map.

$$\begin{aligned} &\forall v_r \in \mathbb{V} \wedge \exists m \in \mathbb{M}, v_s \in \mathbb{V} \wedge recv(v_r, v_s, m, t) \Rightarrow \\ &(rebroadcast(v_r, m, t) \Leftrightarrow dist(v_r, v_s) > d_{min} \vee (\exists j \in \mathbb{J} \wedge dist(v_r, j) < th_j)) \end{aligned} \tag{4.2}$$

Equation 4.3 contains the operation of the eMDR algorithm. The main difference between eSBR and eMDR lies on the number of vehicles allowed to retransmit in junctions. Whereas all the vehicles located in junctions are allowed rebroadcasting in eSBR, eMDR only allows one vehicle per junction as a forwarding node. To achieve this behavior, each vehicle $v_r$ stores a list $\mathbb{N}_r$ containing its neighbors in communication range, built by means of periodic beacons sent by all vehicles. Hence, vehicle $v_r$ only rebroadcasts the message if the distance to sender is greater than $d_{min}$, or if it is located near a junction and it is the closest vehicle to the center of the junction, obtained from its geographical coordinates of GPS integrated maps.

$$\begin{aligned} &\forall v_r \in \mathbb{V} \wedge \exists m \in \mathbb{M}, v_s \in \mathbb{V} \wedge recv(v_r, v_s, m, t) \Rightarrow \\ &(rebroadcast(v_r, m, t) \Leftrightarrow dist(v_r, v_s) > d_{min} \vee \\ &(\exists j \in \mathbb{J} \wedge dist(v_r, j) < th_j \wedge (\nexists v_n \in \mathbb{N}_r \wedge dist(v_n, j) < dist(v_r, j)))) \end{aligned} \tag{4.3}$$

Finally, Equation 4.4 shows the formulation of the NJL algorithm. As shown, NJL ignores the distance between sender and receiver and only allows rebroadcasting if the receiver vehicle is the closest to the geographical center of the junction with respect to its neighbors.




(a) (b) (c)

Figure 4.2: Comparison of different dissemination schemes for VANETs: (a) eSBR, (b) eMDR, and (c) NJL.

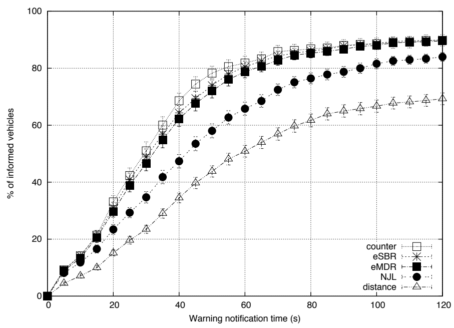
$$\begin{aligned}&\forall v_r \in \mathbb{V} \wedge \exists m \in \mathbb{M}, v_s \in \mathbb{V} \wedge recv(v_r, v_s, m, t) \Rightarrow \\ &(rebroadcast(v_r, m, t) \Leftrightarrow (\exists j \in \mathbb{J} \wedge dist(v_r, j) < th_j \wedge \\ &(\nexists v_n \in \mathbb{N}_r \wedge dist(v_n, j) < dist(v_r, j))))\end{aligned} \tag{4.4}$$

Figure 4.2 shows graphically the differences between eSBR, eMDR, and NJL schemes in a specific VANET scenario, where vehicle $S$ broadcasts a warning message. The line labeled as $d_{min}$ represents the minimum rebroadcast distance used by eSBR and eMDR. Darker vehicles will be allowed to forward the messages received from $S$, and it is noticeable how eSBR is the less restrictive scheme, whereas NJL is the most restrictive one, and thus more suitable for scenarios with a high vehicle density.

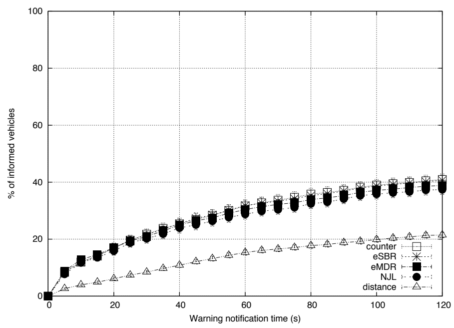
### 4.4.2 Metric 1: Percentage of Informed Vehicles

During the warning message dissemination process, the most important objective to accomplish consists on informing the highest number of vehicles in the shortest time possible. In particular, to better assess our proposal, we performed several experiments using roadmaps with different features, as well as varying the density of vehicles. Figures 4.3 and 4.4 present the evolution of the dissemination process in terms of informed vehicles for the maps of San Francisco and Valencia under four different vehicle densities: 25, 100, 150, and 250 vehicles/km$^2$.

It is noticeable how the roadmap topology and the vehicle density are determinant factors affecting the performance of the dissemination process. In general, the dissemination process develops faster (i.e., more vehicles are informed during a same period) when the vehicle density increases, independently from the broadcast scheme used, and especially in complex roadmaps. For sparse urban scenarios, the counter-based scheme provides the best results in terms of informed vehicles, whereas for densities above 150 vehicles/km$^2$, the dissemination process presents a very similar behavior for all the selected broadcast schemes. The exception is the distance-based scheme in the map of Valencia, which proved to be very ineffi-




(a)

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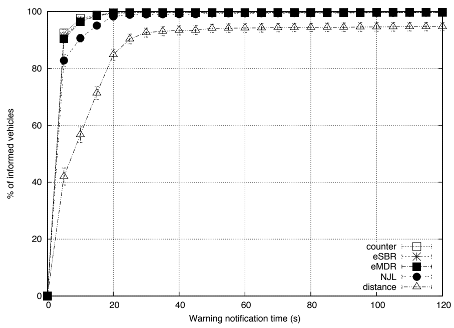
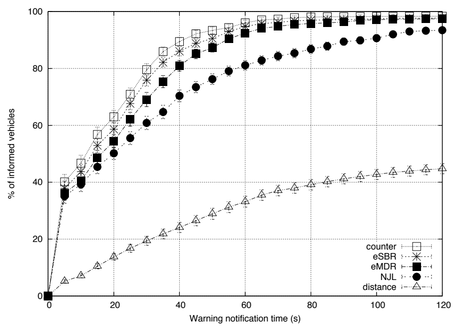
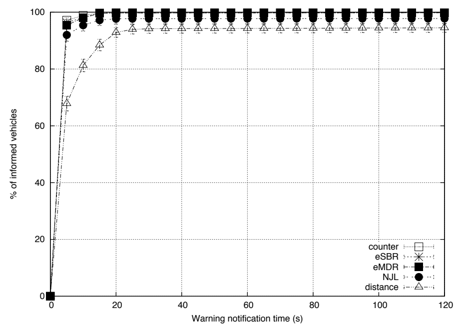



(b)

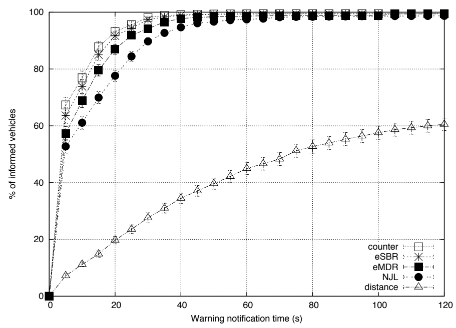



(d)

Figure 4.3: Percentage of informed vehicles in San Francisco for: (a) 25, and (b) 100, vehicles/km$^2$, as well as in Valencia for: (c) 25, and (d) 100 vehicles/km$^2$.




(a)

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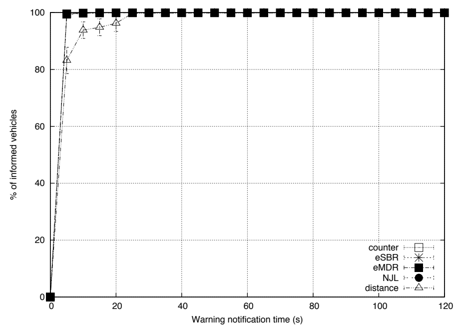


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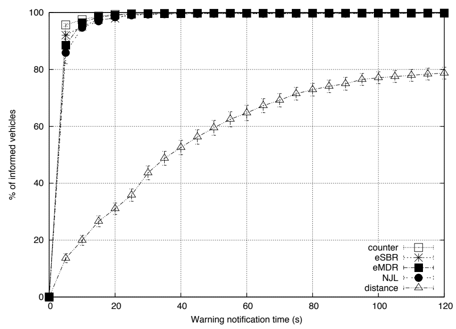



(d)

Figure 4.4: Percentage of informed vehicles in San Francisco for: (a) 150, and (b) 250 vehicles/km$^2$, as well as in Valencia for: (c) 150, and (d) 250 vehicles/km$^2$.

cient due to the high amount of obstacles interfering with the radio signal, as this roadmap presents a higher complexity (the SJ Ratio is higher than San Francisco).

In addition, we corroborated that simple and regular city profiles, like San Francisco, allow an easier propagation of the radio signal, increasing the number of informed vehicles at a given time. However, the most restrictive schemes, such as NJL, require a very high density of vehicles to achieve an efficiency similar to other dissemination schemes.

These results indicate that basing the broadcast policy selection only on the percentage of informed vehicles (e.g., after some minutes) could lead to wrong decisions that could seriously affect the efficiency of the system, justifying the need for additional metrics to perform the broadcast scheme selection. Additionally, to better characterize the dissemination process, we consider that the broadcast selection should account for the percentage of informed vehicles at different time instants ($Inf_T$). Specifically, we propose to measure the percentage of vehicles receiving warning messages after 10, 30, and 120 seconds (i.e., $Inf_{10}$, $Inf_{30}$, and $Inf_{120}$) since it is important to account for the first seconds from the time when the dangerous situation started being notified until the dissemination stabilizes. This provides information about both the speed and completeness of the dissemination process. The first 10 seconds provide a good reference of the dissemination speed, the second period (30 seconds) offers a balance between dissemination speed and the completeness, and the state of the scenario after 120 seconds shows the stationary value when no evolution is observed. These three values are combined using a weighted average, thereby obtaining a single value representing the efficiency of the dissemination process ($P_{inf}$). In our system, the weights applied to the values collected during the different time intervals are 0.5 (10 seconds), 0.3 (30 seconds), and 0.2 (120 seconds), respectively, since the stationary values of the different broadcast schemes do not tend to vary significantly, and the most noticeable differences occur during the first seconds of the process.

### 4.4.3 Metric 2: Messages Received per Vehicle

The number of messages produced by a given dissemination scheme may become very important in VANETs due to the high number of messages sent and received by the vehicles involved. This could increase channel contention and the frequency of collisions. Therefore, a reduction of the number of messages received per vehicle under this situation, without reducing the percentage of informed vehicles, will improve the warning message dissemination process, allowing other applications sharing the channel to operate adequately. To this end, it is necessary to evaluate the different dissemination schemes, taking into account the number of messages received by each vehicle in order to select the optimal scheme for each particular scenario.

Figure 4.5 shows the number of messages received per vehicle in San Francisco and Valencia. Notice that the selected dissemination scheme presents a determinant influence over the amount of messages received; some of them show only a fraction of the messages required by other schemes. In general, the counter-based scheme produces the highest number of messages, whereas the distance-based scheme is the most restrictive one. As we might suppose, the NJL scheme

**Algorithm 1** Optimal Broadcast Selection.

**input** : $\mathbb{B}$: set of broadcast schemes
**input** : $Inf_{10}(b), Inf_{30}(b), Inf_{120}(b)$: percentage of informed vehicles after 10, 30, and 120 seconds
**input** : $M_{recv}(b)$: number of messages received per vehicle
**output** : $Optimal_{bcast}$: optimal scheme in terms of informed vehicles and messages received

```
/* Step 1: Maximize percentage of informed vehicles */
```
**forall** $b \in \mathbb{B}$ **do**
  $P_{inf}(b) = Inf_{10}(b) \cdot 0.5 + Inf_{30}(b) \cdot 0.3 + Inf_{120}(b) \cdot 0.2;$
$max_{inf} = max(P_{inf}(b)) \ \forall \ b \ \in \mathbb{B}$
$\mathbb{C} = \{\}$
**forall** $b \in \mathbb{B}$ **do**
  **if** $(max_{inf} - P_{inf}(b)) < 10\%$ **then** $\mathbb{C} = \mathbb{C} \cup \{b\}$

```
/* Step 2: Minimize received messages */
```
$min_{recv} = min(M_{recv}(b)) \ \forall \ b \ \in \mathbb{C}$
**forall** $b \in \mathbb{C}$ **do**
  $dev_{inf}(b) = max_{inf} - P_{inf}(b)$
  $dev_{recv}(b) = \frac{M_{recv}(b) - min_{recv}}{min_{recv}}$

```
/* Step 3: Selection of the optimal broadcast scheme */
```
$Optimal_{bcast} = \arg\min_{b \in \mathbb{C}} \ (dev_{inf}(b) \cdot K + dev_{recv}(b)) \ \forall \ b \ \in \mathbb{B}$

produces the smallest amount of messages of all the schemes which used the information topology of the map to select the forwarding nodes. Note that NJL generates fewer messages than the distance-based algorithm in San Francisco's high density scenarios. Again, the features are determinant for the performance of the system. Simple maps allow a faster dissemination at the cost of noticeably increasing the number of messages received per vehicle, thereby increasing the probability of broadcast storms. Thus, more restrictive schemes are recommended for this kind of roadmaps.

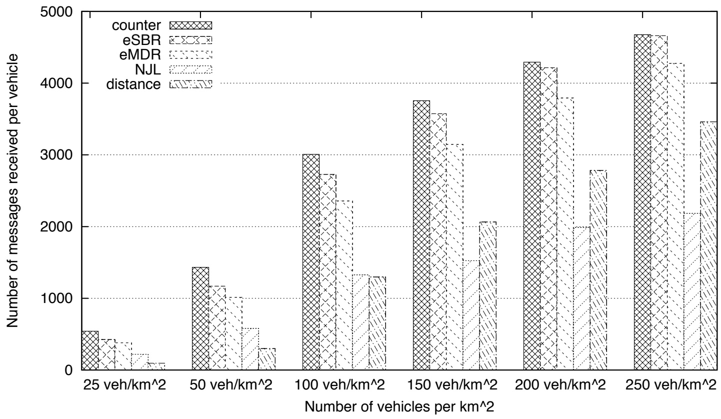
We consider that the number of messages received per vehicle ($M_{recv}$) is an important metric to be accounted for when ensuring an efficient dissemination process. If the wireless channel is saturated with packets, the high degree of contention and the occurrence of collisions will reduce the performance of the process, producing broadcast storms. Hence, the number of messages must remain as low as possible without compromising the dissemination efficiency.

### 4.4.4 Optimal Broadcast Selection Algorithm

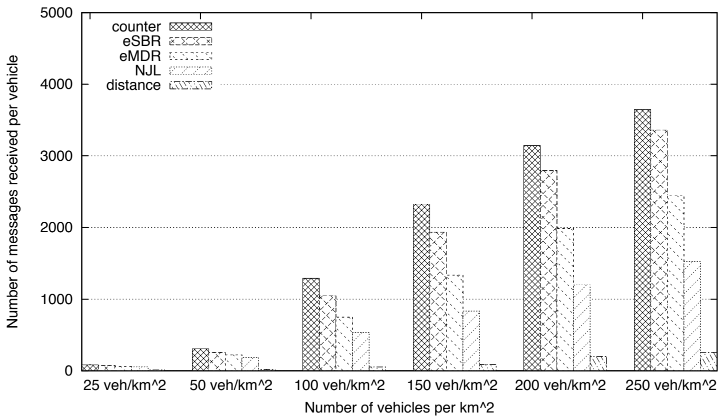
The core of our RTAD system is the Optimal Broadcast Selection Algorithm which makes use of the two metrics presented before ($P_{inf}$ and $M_{recv}$) to select the broadcast scheme to be used on each particular situation. Specifically, it works following a three step process, as shown in Algorithm 1:

- *Step 1*: For each considered broadcast scheme, the first metric ($P_{inf}$) is computed, and the scheme with the highest percentage of informed vehicles in the shortest time is selected. Due to the importance of this metric, only the dissemination schemes with a deviation lower than 10% with respect to the best one are considered for the second step of the algorithm, and then included in set $\mathbb{C}$.

- *Step 2*: Considering only the broadcast schemes in $\mathbb{C}$, the scheme producing




(a)




(b)

Figure 4.5: Number of messages received per vehicle when varying the broadcast scheme and the vehicular density in: (a) San Francisco and (b) Valencia.

the lowest number of messages per vehicle ($M_{recv}$) is obtained, in order to reduce the probability of broadcast storms, and the percentage variation with respect to this value is computed for each scheme.

- *Step 3*: The optimal scheme will be selected as the one minimizing the deviation with respect to both the maximal $P_{inf}$ and the minimal $M_{recv}$. Depending on the vehicle density, our proposed algorithm adapts its behavior. Hence, it is more important to reduce the number of messages received in high vehicle densities, whereas increasing the number of informed vehicles becomes more important in sparse scenarios, where the number of messages received is not a problem. Specifically, our algorithm varies the degree of importance of the two metrics (i.e., $P_{inf}$ and $M_{recv}$) by using the $K$ value, calculated as follows:

$$K = \frac{100}{density\ of\ vehicles} \tag{4.5}$$

In particular, we used the value of reference 100 to compute $K$, since our experiments showed that the differences in terms of informed vehicles decrease noticeably for densities above 100 vehicles/km$^2$ (see Figure 4.3), and, hence, a higher weight is assigned to the number of messages received when this density is exceeded.

Table 4.3 contains an example of the performance of our broadcast scheme selection algorithm. Specifically, it shows the results obtained for Valencia when simulating 100 vehicles/km$^2$. All the values are obtained as the average of 50 repetitions for each configuration. It is noticeable how only three of the selected schemes are considered after the first step of the algorithm (i.e., the counter-based, the eSBR, and the eMDR broadcast schemes). Since the eMDR produces the lowest number of messages while maintaining a high percentage of informed vehicles in a small time period, our algorithm considers it as the optimal broadcast scheme for this particular scenario.

Table 4.4 shows the selected broadcast scheme for each of the simulated scenarios according to our proposed Optimal Broadcast Selection Algorithm. Notice that the proposed NJL scheme is selected as the optimal one in most cases, especially under high vehicle densities or simple maps with a small SJ ratio, where the radio signal can cover large distances and broadcast storms are prone to occur. On the contrary, eMDR and eSBR schemes offer better results in scenarios where broadcast storms are not a problem, and the main objective is informing as many vehicles as soon as possible.

It is remarkable that almost all the schemes selected by our proposed algorithm rely on topology information to select the most appropriate forwarding vehicle, highlighting the importance of this factor in the warning dissemination process. In fact, broadcast schemes that only make use of the distance between the sender and the receiver, or which only focus on avoiding repeated messages, present a worse trade-off between performance and the amount of messages required. We also observed an anomaly in the results obtained in Table 4.4 corresponding to the map of Madrid. The selected scheme when simulating 25 vehicles/km$^2$ is the

Table 4.3: Simulation results for 100 vehicles/km$^2$ in Valencia.

| **Broadcast** | $Inf_{10}$ | $Inf_{30}$ | $Inf_{120}$ | $P_{inf}$ | $dev_{inf}$ | $\mathbb{C}_1$ **(Step 1)** | $M_{recv}$ | $dev_{recv}$ **(Step 2)** | $dev_{Tot}$ | **Optimal (Step 3)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Counter** | 46.6% | 79.5% | 98.3% | 66.81 | **0%** | ✔ | 1196 | **77.9%** | **75.55** | ✖ |
| **Distance** | 7.10% | 19.4% | 44.7% | 18.31 | **72.59%** | ✖ | - | - | - | - |
| **eSBR** | 43.7% | 75.8% | 97.7% | 64.13 | **4.01%** | ✔ | 940 | **39.87%** | **43.89** | ✖ |
| **eMDR** | 40.4% | 69% | 97.4% | 60.38 | **9.62%** | ✔ | 672 | **0%** | **9.62** | ✔ |
| **NJL** | 39.2% | 60.8% | 93.4% | 56.52 | **15.40%** | ✖ | - | - | - | - |

Table 4.4: Broadcast Scheme Selected According to our Optimal Broadcast Selection Algorithm.

| City | SJ Ratio | Vehicle Density (veh./km$^2$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 25 | 50 | 100 | 150 | 200 | 250 |
| **Rome** | 1.387 | eSBR | eSBR | eSBR | eSBR | NJL | NJL |
| **Valencia** | 1.267 | eMDR | eMDR | eMDR | eMDR | NJL | NJL |
| **Sydney** | 1.071 | eMDR | eMDR | eMDR | NJL | NJL | NJL |
| **Amsterdam** | 1.031 | eMDR | eMDR | NJL | NJL | NJL | NJL |
| **Los Angeles** | 0.938 | eMDR | eMDR | NJL | NJL | NJL | NJL |
| **San Francisco** | 0.886 | eMDR | eMDR | NJL | NJL | NJL | NJL |
| **Madrid** | 0.878 | Counter | eMDR | NJL | NJL | NJL | NJL |

counter-based one, while the overall trend indicates that the chosen one should be the eMDR scheme. This is due to the thresholds selected for Step 1 of the algorithm, where only those schemes with less than 10% variation with respect to the maximum value are considered. The eSBR and eMDR schemes achieve a value of 10.2% and 10.51% variation, respectively, which causes them to be ignored after the first step of the selection algorithm. This indicates that the use of fixed thresholds may lead to inaccurate decisions in some specific cases. We consider that a possible improvement of the broadcast selection algorithm could be using fuzzy logic to decide upon protocol adequacy, thereby avoiding those cases where values close to the threshold are completely ignored.

## 4.5 RTAD: Real-time Adaptive Dissemination System for VANETs

As previously commented, the main objective of this work is to propose a real-time adaptive dissemination system in which each vehicle dynamically adopts a specific dissemination scheme according to each particular scenario. Based on the conclusions drawn in Section 4.4, now we present RTAD, our adaptive approach to improve message dissemination in VANETs.

Figure 4.6 shows how our proposal has been developed. First, we analyzed the different broadcast dissemination schemes in order to determine the optimal scheme to each specific situation. According to this analysis, we proposed a real-time adaptive system that makes each vehicle to automatically adopt the optimal dissemination scheme in order to fit the warning message delivery policy to each specific situation.

Algorithm 2 details the RTAD operation. As shown, RTAD determines which dissemination approach to use according the SJ Ratio and the vehicle density estimated. The SJ Ratio is automatically calculated by each vehicles by means of its geographical coordinates of GPS and the integrated maps, whereas the vehicle density is estimated in real time. According to our RTAD algorithm, each vehicle would adopt the optimal dissemination scheme in order to improve the dissemi-

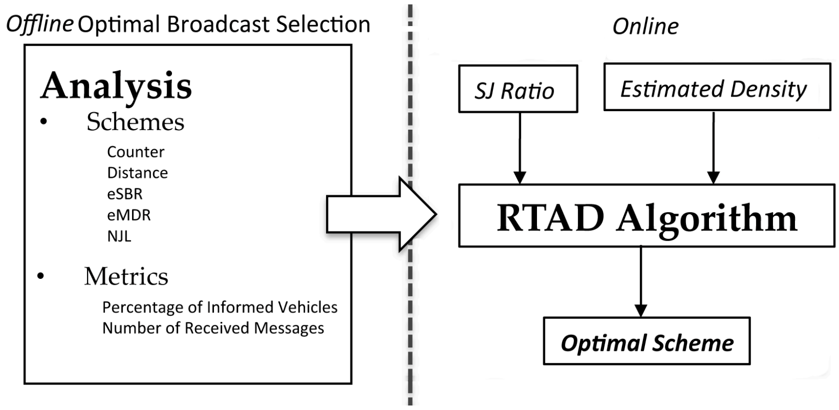



Figure 4.6: Details of our Real-time adaptive dissemination system.

**Algorithm 2** RTAD Implementation

**input** : $D$ - estimated density (vehicles/km$^2$)
**input** : $SJR$ - SJ Ratio
**output** : $Optimal_{bcast}$ - optimal scheme
**if** *(($D > 175$) OR ($D > 125$ AND $SJR < 1.1$) OR ($D > 75$ AND $SJR < 1.05$))* **then**
  return NJL;
**else if** *($SJR > 1.3$ AND $D < 175$)* **then**
  return eSBR
**else**
  return eMDR

nation process. The computational cost of this algorithm is very low, hence the overhead is almost negligible.

As stated above, our proposed RTAD system relies on the Optimal Broadcast Selection Algorithm to adapt the dissemination process to the specific characteristics at a given time. Additionally, the Optimal Broadcast Selection Algorithm needs to estimate the vehicle density to select the most appropriate broadcast scheme. In particular, density estimation is a determinant step when establishing the optimal distribution algorithm.

In this work we use a neighbor-based density estimation scheme, which accurately estimates the vehicle density, allowing our system to select the most adequate dissemination scheme at any time.

In Chapter 3, we proposed a method to calculate the density depending on the number of beacons received by vehicle. Although this method introduces a small density estimation error, in this chapter we modified it to increase its accuracy, and also to make its integration in our adaptive algorithm feasible. Specifically, the RTAD system uses the number of neighbors, instead of the number of beacons received, to estimate the vehicle density.

We call neighbors those vehicles that are reachable by one-hop messages, without requiring any additional rebroadcast, i.e., they are within the communication

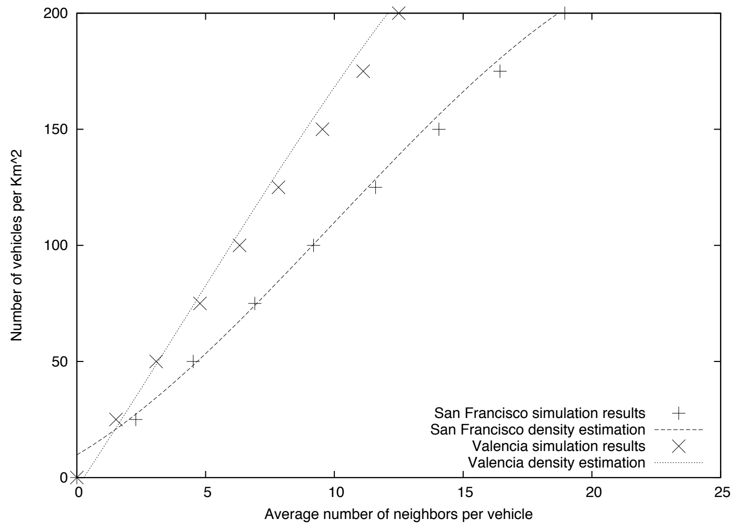



Figure 4.7: Simulation results and vehicle density estimation in San Francisco and Valencia.

range of the sender vehicle and the signal transmission is not blocked by any obstacle such as buildings. In our system, all the vehicles considered maintain a neighbor list that is built by using the beacons exchanged periodically among the nodes, avoiding any additional channel overhead. Whenever a new beacon is received, each vehicle checks its neighbor list to determine if the sender is a new neighbor, thereby adding this vehicle to the list. The neighbors' list is updated when new beacons are not received from a former neighbor after 2 seconds. In that case, the neighbor is removed from the list.

Our new density estimation approach, based on the number of neighbors, yields more accurate results, presenting a lower sum for the squared absolute error (approximately 5.098E+03, whereas the beacon-based approach results in 6.332E+03 [SFG$^+$13a]). Figure 4.7 shows the density data obtained in the simulation for the roadmaps of San Francisco and Valencia, as well as the values estimated according the SJ Ratio (roadmap complexity) and the number of neighbors. As shown, we achieve a good fit for the values obtained in the simulations, especially in San Francisco.

## 4.6 RTAD Performance Evaluation

To assess the performance of our proposal, we have performed experiments using several cities with different characteristics. In this section we present the results obtained in four cities: in one hand, we used Amsterdam and Los Angeles which were previously used to calibrate the proposal. On other hand, we also tested

Sydney but with the aim of increasing the level of realism, we also considered that vehicles are not uniformly distributed since, in a real town, traffic is not uniformly distributed; instead, there are downtowns or points of interest that may attract vehicles. Specifically, we considered a downtown of 750x750 meters located at the center of the map, which presents a higher density of vehicles. Finally, to better assess our proposal, we have also simulated a bigger area (i.e., 9 $km^2$) of Santiago de Chile. This roadmap presents a SJ Ratio of 0.972, so it can be considered a medium complexity map. Additionally, in these experiments we considered two different downtowns, the first one in the top right corner, and the second one in the bottom left corner.

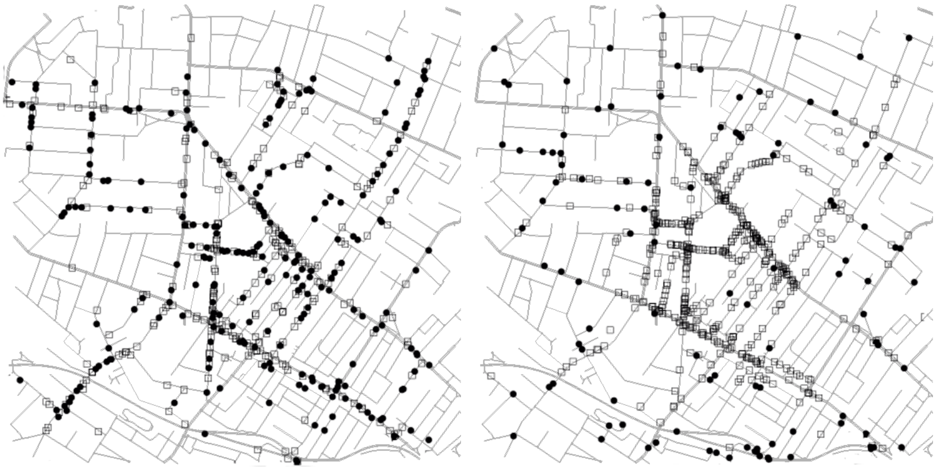
Figure 4.8 shows the dissemination scheme selected by each vehicle at two different instants of the simulation (1 and 60 seconds after the simulation start), when simulating 150 vehicles/$km^2$ in Sydney. As shown, only 1 second after the simulation starts, the vehicles immediately proceed to adapt their broadcast mode (in particular, they use eMDR and NJL), according to the roadmap topology and the number of neighbors detected at this moment (as previously presented in Table 4.4). Note that this situation evolves, and after 60 seconds (see Figure 4.8.b), most of the vehicles are using the NJL scheme (a more restrictive dissemination scheme) since the warning messages can easily reach more vehicles in high density areas; however, isolated vehicles still use eMDR since they try to inform more vehicles without provoking broadcast storms.

Figure 4.9 shows the broadcast used by each vehicle 30 seconds after the beginning of the simulation. As expected, most of the vehicles located within a downtown use the NJL scheme, whereas the vehicles in the outskirts use a less restrictive dissemination policy; in particular, they use the eMDR scheme. Since the vehicle density is not uniformly distributed in the scenario, by using RTAD, each vehicle adapts its dissemination policy to better inform the rest of vehicles while significantly reducing the number of messages sent, thus avoiding overloading the channel. Next, in order to assess RTAD goodness, we compare our approach with respect to two static dissemination schemes (eMDR and NJL), and three adaptive dissemination systems (UV-CAST, DV-CAST, and FDPD), previously proposed in the literature.

### 4.6.1 RTAD vs. Static Dissemination Schemes

Static systems, unlike adaptive or dynamic systems, are systems that remain substantially unchanged through out time. Regarding vehicular environments, static broadcast schemes always use the same broadcast dissemination policy, without changing their mode of operation. Thus, they are not able to dynamically adapt their behavior to the specific features of the environment (e.g., different vehicle densities, or time-varying conditions).

In this section we compare the performance of our adaptive proposal against existing static dissemination schemes, such as the NJL and the eMDR schemes. Table 4.5 and Figure 4.10 show the average results obtained by each broadcast scheme in terms of: (i) $P_{Inf}$, the value that represents the efficiency of the dissemination process according the percentage of informed vehicles, and (ii) $M_{recv}$, the number of messages received by each vehicle, when varying the vehicle density



(a) (b)

Figure 4.8: Broadcast scheme used by each vehicle in Sydney when simulating 150 veh./km$^2$ at: (a) 1 s., and (b) 60 s. after simulation start, respectively. The eMDR is represented with filled dots, and the NJL with empty squares.

Figure 4.9: Broadcast scheme used by each vehicle in Santiago de Chile when simulating 100 veh./km$^2$, 30 s. after the simulation start. The eMDR scheme is represented with filled dots, and the NJL scheme with empty squares.

Table 4.5: Performance of the different dissemination schemes when varying the vehicle density and the city roadmap.

| v/km$^2$ | | **Amsterdam** | | **Los Angeles** | | **Sydney** | |
|---|---|---|---|---|---|---|---|
| | **Bcast** | $P_{Inf}$ | $M_{recv}$ | $P_{Inf}$ | $M_{recv}$ | $P_{Inf}$ | $M_{recv}$ |
| 25 | **RTAD** | 27.26 | 154.08 | 45.01 | 261.43 | 25.30 | 112.55 |
| | **NJL** | 23.84 (-3.42%) | 89.55 (-41.9%) | 36.12 (-8.89%) | 163.81 (-37.3%) | 22.03 (-3.27%) | 71.24 (-36.7%) |
| | **eMDR** | 27.52 (+0.26%) | 159.19 (+3.3%) | 44.48 (-0.53%) | 268.00 (+2.5%) | 25.33 (+0.03%) | 113.21 (+0.6%) |
| 50 | **RTAD** | 50.77 | 470.20 | 81.89 | 789.70 | 44.98 | 360.68 |
| | **NJL** | 44.75 (-6.02%) | 290.26 (-38.3%) | 68.62 (-13.27%) | 556.89 (-29.5%) | 39.07 (-5.91%) | 231.58 (-35.8%) |
| | **eMDR** | 52.89 (+2.12%) | 666.49 (+41.7%) | 81.51 (-0.38%) | 1017.42 (+28.8%) | 45.95 (+0.97%) | 458.67 (+27.2%) |
| 100 | **RTAD** | 90.06 | 1051.98 | 96.80 | 1294.83 | 76.46 | 816.05 |
| | **NJL** | 86.38 (-3.68%) | 877.53 (-16.6%) | 93.89 (-2.91%) | 1113.21 (-14.0%) | 70.90 (-5.56%) | 631.03 (-22.7%) |
| | **eMDR** | 90.11 (+0.05%) | 1786.42 (+69.8%) | 97.88 (+1.08%) | 2220.96 (+71.5%) | 79.29 (+2.83%) | 1344.19 (+64.7%) |
| 150 | **RTAD** | 96.78 | 1411.88 | 99.57 | 1605.60 | 88.53 | 1092.46 |
| | **NJL** | 89.99 (-6.79%) | 1173.85 (-16.9%) | 99.39 (-0.18%) | 1457.89 (-9.2%) | 86.62 (-1.91%) | 918.73 (-15.9%) |
| | **eMDR** | 96.90 (+0.12%) | 2538.63 (+79.8%) | 99.57 (+0.00%) | 3096.48 (+92.9%) | 90.69 (+2.16%) | 2095.19 (+91.8%) |
| 200 | **RTAD** | 98.17 | 1666.42 | 99.70 | 1773.84 | 96.03 | 1331.97 |
| | **NJL** | 98.70 (+0.53%) | 1599.83 (-4.0%) | 99.57 (-0.13%) | 1602.39 (-9.7%) | 92.11 (-3.92%) | 1136.45 (-14.7%) |
| | **eMDR** | 99.00 (+0.83%) | 3284.05 (+97.1%) | 99.70 (+0.00%) | 3738.32 (+110.7%) | 94.04 (-1.99%) | 2661.47 (+99.8%) |

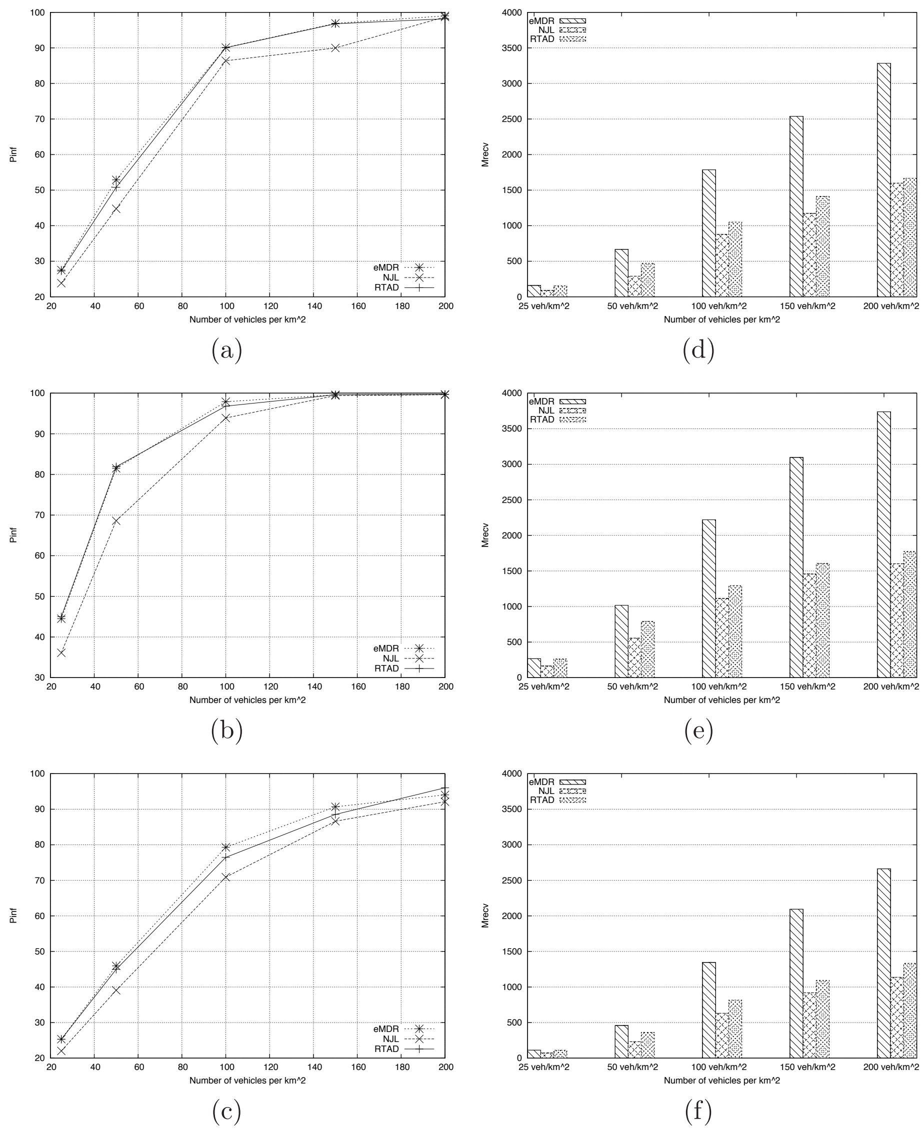



Figure 4.10: Informed vehicles ($P_{Inf}$) and Messages received ($M_{recv}$) when varying the vehicle density and the city roadmap: Amsterdam ((a) and (d)), Los Angeles ((b) and (e)), and Sydney ((c) and (f)).

and the city roadmap.

As shown, under low vehicle densities (i.e., 25 vehicles/km$^2$), the performance of RTAD is close to the results obtained by the most appropriate static broadcast scheme in sparse environments, i.e., the eMDR scheme. There are no significant changes in terms of informed vehicles, whereas there is a slight reduction in the number of messages received in all the tested scenarios when comparing the two schemes. The performance of the NJL scheme is worse under low vehicle densities; this becomes especially noticeable in the map of Los Angeles.

As the vehicle density increases, we see how the RTAD scheme still provides results very close to eMDR in terms of notified vehicles, although it only produces a fraction of the messages used by eMDR. The NJL scheme is the scheme that achieves the lowest value in the number of received messages; however, RTAD compensates the additional messages introduced by increasing the percentage of informed vehicles, which is clearly visible in the results obtained with the maps of Sydney and Amsterdam.

Finally, for the highest densities tested, RTAD is able to combine the best features of the two static schemes: the percentage of informed vehicles is very close to eMDR, but it generates an amount of messages comparable to those generated by NJL. Note that RTAD informs more vehicles than eMDR in the Sydney scenario under the highest density (200 vehicles/km$^2$), whereas the number of messages received is reduced by half. It is remarkable how the RTAD scheme provides optimal results in all situations compared to different static schemes, ranging from low densities with complex maps, to high densities in simple scenarios. By prioritizing the percentage of vehicles notified, and by reducing the number of messages as much as possible, it is able to reduce the channel overhead and optimize the message dissemination process.

### 4.6.2 RTAD vs. Adaptive Dissemination Schemes

Adaptive systems are able to respond to environmental changes, adapting its operation mode so as to face these changes in the best possible way. Regarding vehicular environments, adaptive schemes are able to adapt the dissemination policy to the specific conditions of the scenario, thereby improving the dissemination process, or reducing the channel contention. In this section we compare the performance of our proposal against other existing adaptive dissemination schemes: DV-CAST [TWB10], UV-CAST [VTB11], and FDPD [STC+06].

- Tonguz et al. [TWB10] presented the Distributed Vehicular Broad-CAST (DV-CAST) protocol. Specifically, DV-CAST is a distributed broadcast protocol that relies only on local topology information for handling broadcast messages in VANETs. DV-CAST handles the broadcast storm and the disconnected network problems simultaneously, while incurring a small amount of additional overhead. In particular, the DV-CAST protocol relies on local topology information (i.e., a list of one-hop neighbors) as the main criterion to determine how to handle message rebroadcasting, adapting the dissemination process depending on the density of neighbor vehicles, their position, and their direction. In our simulations we used the weighted p-persistence broadcast suppression technique, as it was the technique selected by authors [TWB10].

- Viriyasitavat et al. [VTB11] proposed the Urban Vehicular broadCAST (UV-CAST) protocol to reduce the broadcast storm problem while solving disconnected network problems in urban VANETs. The UV-CAST algorithm selects different mechanisms for message dissemination in VANETs, differentiating between well-connected and disconnected network regimes. Vehicles in well-connected regimes rebroadcast incoming messages after a wait time if no redundant messages are received. Vehicles under disconnected regimes must decide if they are suitable for the Store-Carry-Forward (SCF) task, forwarding the message whenever they meet new neighbors. The SCF task is assigned to vehicles that have a small expected time before they detect new neighbors, obtained as the boundary vehicles of the neighbors within communication range.

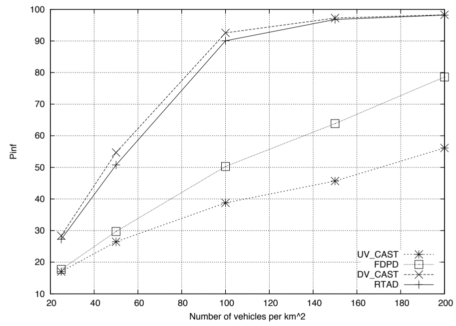
- Sormani et al. [STC+06] defined a message propagation function that encodes information about both target areas and preferred routes. Then, they showed how this function can be exploited in several routing protocols. Specifically, they proposed the Function-Driven Probabilistic Diffusion (FDPD), a probabilistic message dissemination scheme that uses a propagation function calculated by means of the distance between sender and receiver, to determine the forwarding vehicles and reduce the broadcast storm problem.

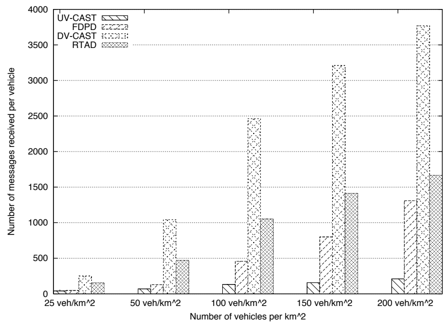
Table 4.6 and Figure 4.11 show the results obtained by each adaptive broadcast system in terms of informed vehicles and number of messages received by vehicle, when varying the vehicle density and the city roadmap.

First of all, it is noteworthy how the UV-CAST scheme is extremely focused on the reduction of messages. It produces the lowest number of messages in all the tested scenarios, up to 90.8% fewer messages received when compared to RTAD. However, this massive reduction presents an important drawback, since it causes a very slow and inefficient dissemination process. Thus, the UV-CAST is an unsuitable scheme for warning message dissemination, where the main objective is to inform as many vehicles as soon as possible. However, this scheme could be useful to disseminate non-critical information, such as advertisements, which do not present the delay requirements associated to traffic safety applications. The DV-CAST scheme obtains results close to the proposed RTAD scheme in terms of informed vehicles. In most of the tested situations the difference between the values obtained by both algorithms is less than 3%, with situations favorable to DV-CAST, especially under low vehicle densities. However, in high vehicle densities, RTAD is able to inform almost the same number of vehicles while considerably reducing the number of messages received per vehicle. Focusing on the number of received messages, we can observe how RTAD is able to reduce the number of messages by more than half in most of the scenarios, especially when the vehicle density increases. This effect makes the RTAD algorithm more robust against broadcast storms, and thus more suitable for environments with a high density of

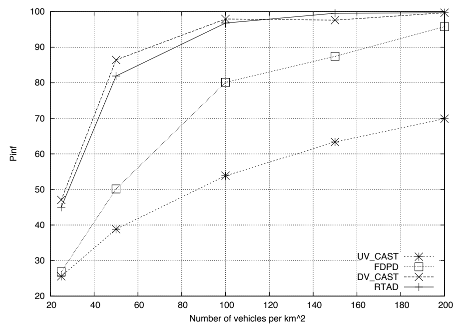
Table 4.6: Performance of the different adaptive dissemination systems when varying the vehicle density and the city roadmap.

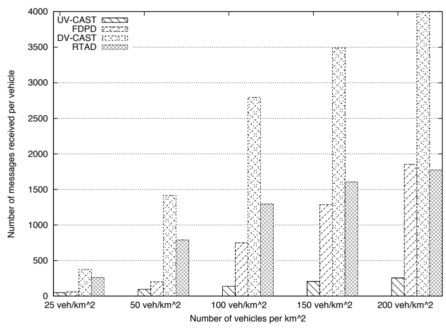
| | | **Amsterdam** | | **Los Angeles** | | **Sydney** | |
|---|---|---|---|---|---|---|---|
| v/km$^2$ | **Bcast** | $P_{Inf}$ | $M_{recv}$ | $P_{Inf}$ | $M_{recv}$ | $P_{Inf}$ | $M_{recv}$ |
| 25 | **RTAD** | 27.26 | 154.08 | 45.01 | 261.43 | 23.30 | 112.55 |
| | **DV-CAST** | 28.39 (+1.13%) | 249.46 (+61.9%) | 47.05 (+2.04%) | 377.98 (+44.6%) | 26.8 (+1.50%) | 170.73 (+51.7%) |
| | **FDPD** | 17.71 (-9.55%) | 45.67 (-70.4%) | 26.84 (-18.17%) | 58.64 (-77.6%) | 16.76 (-8.54%) | 33.51 (.70.23%) |
| | **UV-CAST** | 17.01 (-10.25%) | 39.88 (-74.1%) | 25.57 (-19.44%) | 50.17 (-80.8%) | 18.12 (-7.18%) | 35.17 (-68.8%) |
| 50 | **RTAD** | 50.77 | 470.20 | 81.89 | 789.70 | 44.98 | 360.68 |
| | **DV-CAST** | 54.70 (+3.93%) | 1042.66 (+121.7%) | 86.44 (+2.55%) | 1414.48 (+79.1%) | 48.60 (+3.62%) | 721.30 (+100.0%) |
| | **FDPD** | 29.72 (-21.5%) | 128.53 (-72.7%) | 50.14 (-31.75%) | 200.84 (-74.6%) | 28.14 (-16.84%) | 98.09 (-72.80%) |
| | **UV-CAST** | 26.46 (-24.31%) | 68.63 (-85.4%) | 38.82 (-43.07%) | 95.45 (-87.9%) | 23.27 (-21.71%) | 59.75 (-83.4%) |
| 100 | **RTAD** | 90.06 | 1051.98 | 96.80 | 1294.83 | 76.46 | 816.05 |
| | **DV-CAST** | 92.55 (+2.49%) | 2462.22 (+134.1%) | 97.94 (+1.14%) | 2793.41 (+115.7%) | 80.48 (+4.02%) | 1932.45 (+136.8%) |
| | **FDPD** | 50.28 (-39.78%) | 457.05 (-56.6%) | 80.11 (-16.69%) | 748.76 (-42.2%) | 45.70 (-30.76%) | 357.96 (-56.14%) |
| | **UV-CAST** | 38.77 (-51.29%) | 129.96 (-87.6%) | 53.85 (-42.95%) | 138.10 (-89.3%) | 38.02 (-38.44%) | 98.54 (-87.9%) |
| 150 | **RTAD** | 96.78 | 1411.88 | 99.57 | 1605.60 | 88.53 | 1092.46 |
| | **DV-CAST** | 97.23 (+0.45%) | 3209.42 (+127.3%) | 97.62 (-1.95%) | 3488.61 (+117.3%) | 89.73 (+1.20%) | 2725.15 (+149.5%) |
| | **FDPD** | 63.85 (-32.93%) | 798.94 (-43.4%) | 87.44 (-12.13%) | 1286.34 (-19.9%) | 61.99 (-26.54%) | 685.54 (-37.25%) |
| | **UV-CAST** | 45.69 (-51.09%) | 157.02 (-88.9%) | 63.34 (-36.23%) | 206.13 (-87.2%) | 40.70 (-47.83%) | 100.40 (-90.8%) |
| 200 | **RTAD** | 98.17 | 1666.42 | 99.70 | 1773.84 | 96.03 | 1331.97 |
| | **DV-CAST** | 98.27 (+0.10%) | 3767.27 (+126.1%) | 99.70 (+0.00%) | 4044.44 (+128.0%) | 96.53 (+0.50%) | 3358.09 (+152.1%) |
| | **FDPD** | 78.60 (-19.57%) | 1308.7 (-21.5%) | 95.79 (-3.91%) | 1853.97 (+4.5%) | 71.09 (-24.94%) | 1021.07 (-23.34%) |
| | **UV-CAST** | 56.14 (-42.03%) | 209.64 (-87.4%) | 68.89 (-29.81%) | 254.80 (-85.6%) | 41.59 (-54.44%) | 127.45 (-90.4%) |



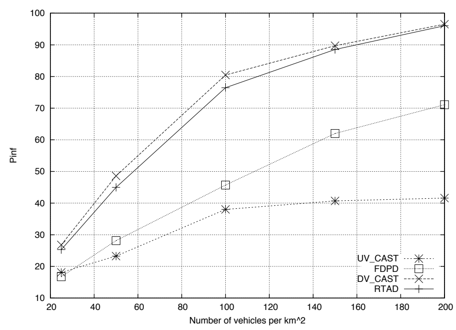



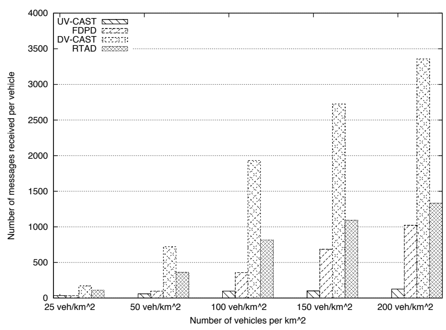

(a) (b)




(c) (d)




(e) (f)

Figure 4.11: Informed vehicles ($P_{Inf}$) and Messages received ($M_{recv}$) when varying the vehicle density and the city roadmap: Amsterdam ((a) and (b)), Los Angeles ((b) and (c)), and Sydney ((c) and (d)).

vehicles. Such environments are more prone to increase the number of messages, thus producing channel contention and packet collisions.

Finally, the FDPD scheme offers intermediate results in terms of informed nodes. It is able to outperform UV-CAST, but it does not reach the values obtained by DV-CAST and RTAD. Regarding the number of messages, there is an exponential increment as vehicle density increases. For example, when simulating 25 veh./km$^2$ in Los Angeles, the number of messages is similar to UV-CAST, whereas increasing the density to 200 veh./km$^2$, it offers values higher than RTAD.

To sum up, the proposed RTAD system is able to inform more vehicles than the UV-CAST algorithm in less time, while maintaining a low number of messages produced compared to DV-CAST. Hence, RTAD achieves an optimal balance between the two metrics (i.e., informed vehicles and messages received), making it suitable for a wide variety of scenarios.

## 4.7 Summary

In this chapter we proposed RTAD, an adaptive warning message dissemination algorithm that selects the optimal broadcast scheme in a VANET scenario based on two different metrics: (i) the percentage of informed vehicles, a particularly determinant factor in warning message dissemination, and (ii) the number of messages received by each vehicle, an important factor which indicates the channel contention and the possibility of broadcast storms during the dissemination of alert messages.

In addition, we presented a new broadcast scheme called Nearest Junction Located (NJL), which was specially designed for scenarios presenting high vehicular densities or simple topologies, where broadcast storms are prone to occur. The NJL scheme is designed to reduce the number of messages received per vehicle without noticeably affecting the percentage of informed vehicles.

Experiments showed how our RTAD system is able to dynamically select the optimal dissemination scheme in all the scenarios, thereby adapting to the specific characteristics of them. Moreover, it outperforms static dissemination schemes as well as existing adaptive dissemination systems such as UV-CAST, FDPD, and DV-CAST. Our adaptive dissemination mechanism allows each vehicle to select the optimal broadcast scheme in real time, thus obtaining better results in terms of percentage of vehicles informed and significantly reducing the number of messages sent, while avoiding overloading the channel and improving the performance of other VANET applications.

# Chapter 5

# Topology-based Broadcast Schemes for Urban Scenarios Targeting Adverse Density Conditions

Vehicular networks support cooperative driving on the road, and have attracted much attention due to the new possibilities they offer to modern Intelligent Transportation Systems. However, research works regarding vehicular networks usually obviate assessing their proposals in scenarios including adverse vehicle densities far from the average values, despite being common in real urban environments.

In this chapter, we study the effect of these hostile conditions on the performance of different schemes providing warning message dissemination. The goal of these schemes is to maximize message delivery effectiveness, something difficult to achieve in adverse density scenarios. We then propose the *Junction Store and Forward* (JSF) and the *Neighbor Store and Forward* (NSF) schemes designed to be used under low density conditions, and the *Nearest Junction Located* (NJL) scheme specially developed for high density conditions. Simulation results demonstrate how our proposals are able to outperform existing warning message dissemination schemes in urban environments under adverse vehicle density conditions. In particular, the JSF reduces the warning notification time up to 40% in low density scenarios, whereas the NJL proved to be the most efficient of the tested schemes under high density conditions, informing almost the same percentage of vehicles, while reducing the number of messages up to 30%.

## 5.1 Introduction

Vehicular ad hoc Networks (VANETs) are wireless communication networks which support cooperative driving among vehicles on the road. Vehicles act as communication nodes and relays, forming dynamic vehicular networks together with other nearby vehicles [NW10, STMZI+10].

The specific characteristics of VANETs favor the development of attractive and challenging services and applications, including road safety, traffic flow management, road status monitoring, environmental protection, and mobile infotainment [JLW13, PIDR11, ZZS+11]. In this chapter we focus on traffic safety and efficient warning message dissemination, where the main goal is to reduce the latency while increasing the accuracy of the information received by nearby vehicles when a dangerous situation occurs.

In safety applications based on vehicular networks, the warning message propagation scheme should be aware of the vehicle density, since lower densities can provoke message losses due to reduced communication capabilities, whereas higher densities may lead to reduced message delivery effectiveness due to serious redundancy, contention, and massive packet collisions caused by simultaneous forwarding, usually known as broadcast storm [TNCS02].

So far, several authors have proposed different dissemination schemes to mitigate broadcast storms [BCSZ10, WTP+07, SRF14, SP08]. However, all of these schemes consider free space environments where no blocking obstacles are considered at all. They have not addressed the impact of buildings and other urban obstacles on the wireless signal propagation in realistic urban scenarios. The consequences derived from those incomplete analyses can be observed when their performance is tested in urban topologies, showing that they are unable to choose suitable relaying vehicles, or proving to be too restrictive to achieve an efficient message dissemination [FGM+12b, SFR11].

In this chapter, we study the performance of typical broadcast dissemination schemes under hostile density conditions, i.e., vehicle densities far from the average values in vehicular environments and especially adverse for message dissemination. We consider that adapting the dissemination policy to the specific environment, accounting for the current vehicular density as well as for the scenario where the vehicles are located, can be beneficial in order to reduce broadcast storm related problems, and also to increase the efficiency of the warning message dissemination process. Based on this analysis, we propose both the *Junction Store and Forward* (JSF) and the *Neighbor Store and Forward* (NSF) schemes designed to be used under low density conditions, as well as the *Nearest Junction Located* (NJL) scheme specially developed for high density conditions. Our main goal is to maximize the message delivery effectiveness, something difficult to achieve in adverse conditions.

The chapter is organized as follows: Section 5.2 reviews existing dissemination schemes related to our proposal. In Section 5.3 we introduce our proposed schemes, i.e., the JSF, the NSF, and the NJL approaches. Section 5.4 shows the simulation environment used to validate our proposed algorithms. Section 5.5 presents and discusses the obtained results under very low and high vehicle density scenarios. Finally, Section 5.6 presents the main conclusions drawn in this chapter.

## 5.2 Related Work

Current research on vehicular networks usually focuses on analyzing scenarios representing common situations characterized by average density values. However, situations with very low or very high vehicle densities are often ignored, whereas they are very common in real vehicular environments. For example, outskirts or suburban areas usually experience density values below 25 vehicles/km$^2$, whereas traffic jams that appear in large cities present densities above 300 vehicles/km$^2$. We consider these scenarios as hostile conditions for vehicular networks, since the efficiency of warning message dissemination processes is noticeably reduced under these circumstances.

In this section we introduce some of the most relevant existing proposals related to message dissemination in Vehicular Networks. Before proposing new dissemination schemes specially suitable for adverse density conditions, we are going to analyze the performance of existing broadcast schemes for VANETs under these conditions, accounting for both low and high vehicle densities. Since the challenges to face in each situation are radically different, a separate study could be beneficial to maximize the performance of the message dissemination system.

### 5.2.1 Low Density Conditions

Vehicular scenarios including very low vehicle densities are frequently found in current roads, especially in residential, rural, and outskirt traffic areas. The main goal when developing an emergency message dissemination system is to inform as many vehicles as possible in a short time period. Additionally, maintaining a low amount of wireless traffic is desirable to avoid the mentioned broadcast storm problem. When the density of vehicles is low, the relative importance of the number of messages received per vehicle is reduced, since the probability of overloading the channel due to the messages interchanged by the low number of vehicles is minimal. Hence, suitable schemes for these situations should focus on forwarding warning messages in order to maximize message delivery, even when the probability of informing new vehicles is low. Some existing dissemination schemes that work more efficiently under low density conditions are the following:

- *Flooding*. This strategy is the simplest broadcast scheme, in which vehicles blindly rebroadcast every message they receive without applying additional control mechanisms. In low density scenarios where the probability of broadcast storms is reduced, flooding represents a good candidate scheme.

- The *Counter-based scheme* [TNCS02]. Initially proposed for Mobile Ad Hoc Networks (MANETs), this scheme aims at mitigating broadcast storms by using a threshold $C$ and a counter $c$ to keep track of the number of times a broadcast message is received. Whenever $c \geq C$, rebroadcast is inhibited.

- The *enhanced Street Broadcast Reduction* (eSBR) [MFC+10]. This scheme is specially designed to be used in VANETs, taking advantage of the information provided by maps and built-in positioning systems, such as the Global Positioning System (GPS). Vehicles are only allowed rebroadcasting messages if they are located far from the sender vehicle, or if the vehicles are located in different streets giving access to new areas of the scenario. The eSBR scheme uses information about the roadmap to avoid blind areas due to the presence of urban structures blocking the radio signal.

- Otha et al. [OOKK11] proposed a new reliable data forwarding mechanism that combines Epidemic routing, and the positioning information and moving direction of a node obtained from Global Positioning System (GPS) to reduce widespread forwarded data packets. The proposed scheme forwards data packets using the Store-Carry-Forward mechanism to the neighboring nodes that are determined by the positioning information and moving direction of a vehicle.

- More recently, Sou and Lee [SL12] presented the Store-Carry-Broadcast (SCB) scheme. The main goal of this scheme is to assist message dissemination by broadcasting over a specific road segment instead of a single vehicle. In the SCB scheme, an opposite vehicle helps to disseminate the safety messages to oncoming vehicles traveling on the reverse lane by broadcasting. Compared with the well-known store-carry-forward scheme in VANETs, the SCB scheme consumes much less network bandwidth in terms of the number of broadcasts performed.

### 5.2.2 High Density Conditions

Another typical adverse scenario occurs when the vehicle density is above 300 vehicles/km$^2$, enough to produce traffic jams, or considerably reduce the speed of vehicles. This effect leads to an increase of the number of vehicles sending warning messages and beacons in a specific area, generating a likely scenario for channel contention and message collisions.

High Density situations usually require more restrictive dissemination schemes that allow reducing the number of messages sent, since the performance of the dissemination process may be highly reduced due to broadcast storms. Among the existing schemes that could face this effect we highlight the following:

- The *Distance-based scheme* [TNCS02]. This scheme accounts for the relative distance $d$ between vehicles to decide whether to rebroadcast or not. When the distance $d$ between two vehicles is short, the additional coverage area of the new rebroadcast is low, and so rebroadcasting the warning message is not recommended. Forwarding is only beneficial when the additional coverage is significant.

- Tseng et al. [TJC+10] proposed a vehicle-density-based emergency broadcast (VDEB) scheme to solve the problem of high overhead in sender-oriented schemes, and long delay in receiver-oriented schemes. Reducing the overhead could help reduce the broadcast storm problem in scenarios with a high vehicle density. However, the VDEB approach only works in one-dimensional scenarios, such as highways, and it is not useful in complex urban environments.

- The *enhanced Message Dissemination for Roadmaps* (eMDR) [FGM+12b]. As an improvement to the eSBR scheme, eMDR increases the efficiency of the system by avoiding multiple forwardings of the same message if nearby vehicles are located in different streets. Specifically, vehicles use the information about the junctions of the roadmap, and only the vehicle closest to the geographic center of the junction, according to the geopositioning system, is allowed to forward the messages received. This strategy aims at reducing the number of broadcasted messages while maintaining a high percentage of vehicles informed.

- Tonguz et al. [TWB10] presented the Distributed Vehicular Broad-CAST (DV-CAST) protocol. Specifically, DV-CAST is a distributed broadcast protocol that relies only on local topology information for handling broadcast messages in VANETs. DV-CAST handles the broadcast storm and the disconnected network problems simultaneously, while incurring a small amount of additional overhead. In particular, the DV-CAST protocol relies on local topology information (i.e., a list of one-hop neighbors) as the main criterion to determine how to handle message rebroadcasting, adapting the dissemination process depending on the density of neighbor vehicles, their position, and their direction.

## 5.3 Dissemination Schemes Proposed

Due to the lack of dissemination schemes specifically designed for adverse density conditions, in this chapter we propose two different approaches specially designed for low and high density scenarios. The main objective is to achieve the highest percentage of informed vehicles in the shortest time possible. On the one hand, in environments with low vehicle densities, frequent network partitioning is a huge problem causing message losses and misinformation. On the other hand, in environments with high vehicle densities, the number of messages on the channel is a problem since they can provoke the well-known broadcast storm problem.

In low vehicle density scenarios, it is useful to store received messages until an optimal forwarding situation is found, instead of simply rebroadcasting messages at the time they are received, i.e., use a Store-and-Forward approach. Depending on the event producing an optimal situation, we propose two different schemes: the *Junction Store and Forward* (JSF) scheme, and the *Neighbor Store and Forward* (NSF) scheme. These schemes require the presence of a neighbor list in each of the vehicles, which is built using the one-hop *beacons* periodically interchanged by the vehicles with information about their position and speed.

In addition, we propose the *Nearest Junction Located* (NJL), a scheme specially designed to reduce the broadcast storm problems in high density scenarios. Unlike NSF, this scheme does not require storing received warning messages or information about neighbors, since the high vehicle density is usually enough to provide good network connectivity. Instead, information about the road topology is used, and only vehicles placed at suitable locations are allowed to forward messages.

### 5.3.1 Junction Store and Forward (JSF)

The JSF scheme is designed to exploit both the Story-Carry-Forward approach and the topology-based dissemination at the same time. Vehicles store the warn-

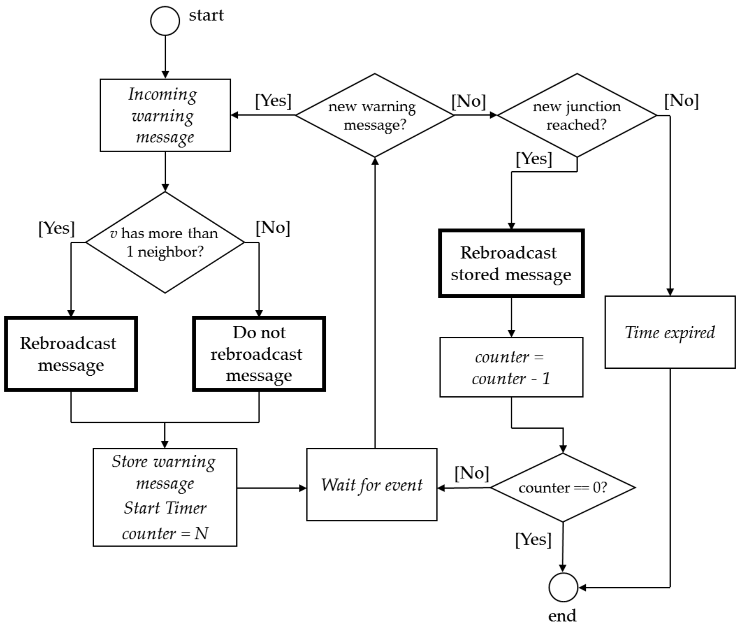



Figure 5.1: JSF dissemination scheme working flowchart.

ing messages they receive during a time period, and forward them when they reach a location in the road topology that maximizes the probability of informing new vehicles. Due to the presence of buildings and other obstacles in urban environments, the optimal locations for message forwarding are the center of the junctions, since they provide line-of-sight access to new streets. This allows increasing the area covered by subsequent retransmissions, reaching areas hardly accessible at first.

The operation of the JSF scheme is summarized in the flowchart shown in Figure 5.1. This scheme requires the presence of a neighbor list in each vehicle, built using the one-hop *beacons* periodically interchanged by the vehicles with information about their position and speed. The beacons are already used by the vehicles in our warning message dissemination process, so maintaining this list does not increase channel overhead. After the reception of a new warning message, the vehicle checks the presence of additional neighbors apart from the sender of the message, so as to avoid sending useless messages where there are no additional neighbors in communication range. Once the message is stored, the vehicle uses the location provided by the integrated GPS system to determine if the vehicle is near a junction. To avoid storing and forwarding old messages (probably useless), a timer is used to dispose these messages.

Vehicles using JSF forward the stored message a finite number of times upon reaching a new junction ($N$). This value is implemented by means of a counter that is updated whenever a new junction is reached. We initially considered three different configurations for the JSF scheme:

- JSF-1: the message is only rebroadcasted within the first junction.

Table 5.1: Performance of the JSF variations under low density conditions in Valencia.

| | **JSF-1** | | | **JSF-3** | | | **JSF-U** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Density** | **% Inf.** | **WNT** | **Msg.** | **% Inf.** | **WNT** | **Msg.** | **% Inf.** | **WNT** | **Msg.** |
| 10 v./km$^2$ | 47.2% | - | 17.2 | 48.4% | - | 17.6 | 46.2% | 111 $s$ | 22.6 |
| 20 v./km$^2$ | 61.1% | 105 $s$ | 57.1 | 64.8% | 69 $s$ | 59.5 | 80.4% | 43 $s$ | 72.8 |
| 30 v./km$^2$ | 83.6% | 41 $s$ | 129.0 | 85.7% | 35 $s$ | 135.6 | 91.8% | 29 $s$ | 158.4 |

Table 5.2: Performance of the JSF variations under low density conditions in San Francisco.

| | **JSF-1** | | | **JSF-3** | | | **JSF-U** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Density** | **% Inf.** | **WNT** | **Msg.** | **% Inf.** | **WNT** | **Msg.** | **% Inf.** | **WNT** | **Msg.** |
| 10 v./km$^2$ | 74.4% | 22 $s$ | 137.5 | 79.4% | 19 $s$ | 138.9 | 84.4% | 19 $s$ | 140.9 |
| 20 v./km$^2$ | 94.3% | 7 $s$ | 393.9 | 94.5% | 14 $s$ | 397.1 | 94.7% | 14 $s$ | 400.2 |
| 30 v./km$^2$ | 96.6% | 2 $s$ | 679.7 | 96.6% | 2 $s$ | 681.4 | 96.6% | 2 $s$ | 688.9 |

- JSF-3: the vehicle rebroadcasts the message in the next three junctions after the message arrival.
- JSF-Unlimited (JSF-U): Junction Store and Forward without limitations, the vehicle rebroadcasts the message every time it arrives at a new junction until the message timer expires.

Tables 5.1 and 5.2 show the results obtained in the roadmaps of Valencia and San Francisco, when comparing the three variations of our JSF scheme in terms of percentage of informed vehicles after 120 seconds ($\%Inf.$), warning notification time required to inform 60% of vehicles ($WNT$), and number of messages received per vehicle ($Msg.$), under the low density simulation environment presented in Section 5.4.

We observe that the differences in the number of messages received per vehicle are minimal, especially in San Francisco, whereas JSF-U is able to increase the percentage of vehicles receiving warning messages and reduce the time required to inform 60% of the vehicles in the scenario, therefore JSF-U is the most effective variant in low density scenarios. Throughout the rest of the paper, we will use the term JSF to refer to the JSF-U variant.

### 5.3.2 Neighbor Store and Forward (NSF)

In order to maximize the performance of the Story-Carry-Forward approach in sparse urban environments, we developed the NSF scheme. This scheme requires a neighbor list that is updated by means of one-hop beacons spread among vehicles, but instead of using information about the roadmap, NSF only relies on neighbor information.

We call neighbors to those vehicles that are reachable by one-hop messages, without requiring any additional rebroadcast, i.e., they are within the communi-

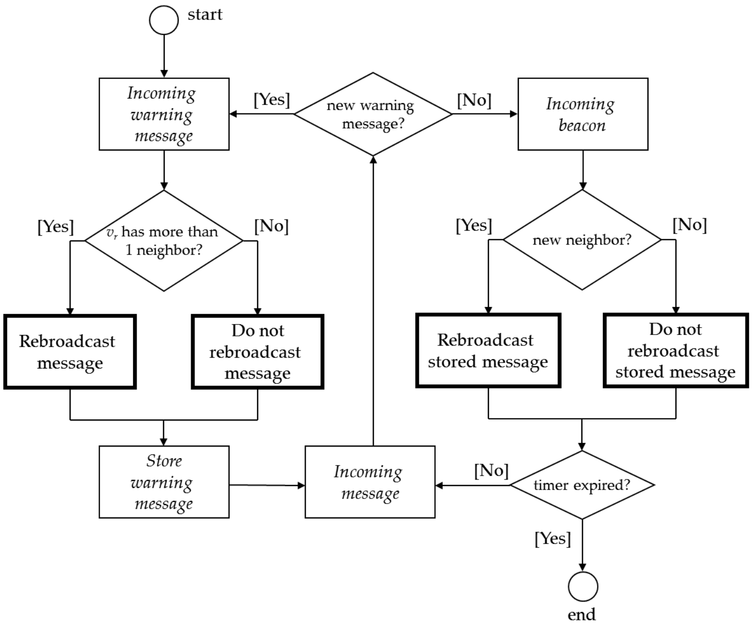



Figure 5.2: NSF dissemination scheme working flowchart.

cation range of the sender vehicle, and the signal transmission is not blocked by any obstacle such as buildings. In our system, all the vehicles considered maintain a neighbor list that is built by using the beacons exchanged periodically by the nodes, avoiding any additional channel overhead. Whenever a new beacon is received, each vehicle checks its neighbor list to determine if the sender is a new neighbor, in which case it will add this new vehicle to the list. The neighbors' list is updated when new beacons are not received from a former neighbor after 2 seconds. In that case, the neighbor is removed from the list.

Figure 5.2 presents the flow chart of the Neighbor Store and Forward (NSF) scheme. In this scheme, after receiving a warning message, the vehicle stores it, and, before rebroadcasting the message, it checks if there are additional neighbor vehicles. Specifically, the vehicle waits to find a new neighbor to rebroadcast the message, i.e., until the vehicle receives a beacon from another vehicle which is not present in the neighbor list. The neighbor list is then updated, and stored messages are forwarded to inform new neighbors about the dangerous situation.

NSF is designed to inform new vehicles as they arrive to the affected area. Hence, the number of messages produced when the NSF scheme is used will be related to the number of vehicles in the scenario.

To better understand the operation of our proposed algorithm, we provide a formal definition of this dissemination scheme using set theory. In the mentioned formulation, the following notation is used:

- $\mathbb{V}$: set of vehicles present in the scenario.
- $\mathbb{N}_i$: set of neighbor vehicles of vehicle $v_i \in \mathbb{V}$.

- $\mathbb{S}_i$: set of warning messages $m \in \mathbb{M}$ stored by vehicle $v_i \in \mathbb{V}$.

The formal definition of NSF requires some basic functions to express events and relationships between the components of the scenario. Specifically, the following functions are required:

- $recv\_beacon(v_r, v_s, t)$: vehicle $v_r$ receives a one-hop beacon from vehicle $v_s$ at time $t$.

- $rebroadcast(v, m, t)$: vehicle $v$ broadcasts a warning message $m$ at time $t$.

Equation 5.1 describes how the NSF algorithm behaves after storing a warning message. As can be observed, NSF only rebroadcasts stored messages when a new vehicle is detected, i.e., those vehicles which are currently not included in the neighbor list.

$$\begin{aligned} &\forall v_r \in \mathbb{V} \wedge \exists v_s \in \mathbb{V} \wedge recv\_beacon(v_r, v_s, t) \wedge \exists m \in \mathbb{S}_r \Rightarrow \\ &(rebroadcast(v_r, m, t) \wedge \mathbb{N}_r = \mathbb{N}_r \cup \{v_s\} \Leftrightarrow v_s \notin \mathbb{N}_r) \end{aligned} \tag{5.1}$$

### 5.3.3 Nearest Junction Located (NJL)

Some dissemination schemes, such as eMDR, have proved to be effective at reducing broadcast storms in typical urban environments. However, the number of messages produced can be excessive in high vehicle density scenarios. Simpler schemes (i.e., that do not account for the effect of obstacles in signal propagation), such as the distance-based scheme offer a reduced number of messages but do not achieve optimal results in terms of informed vehicles in most scenarios. In addition, Store-and-Forward schemes are not usually necessary, due to the lower frequency of partitions in highly congested networks [FGM+12b].

To cope with these deficiencies, we proposed a dissemination scheme called *Nearest Junction Located* (NJL) previously introduced in Section 4.4.1. Unlike existing approaches, NJL is completely based on the topology of the roadmap where the vehicles are located, allowing vehicles to rebroadcast a message only if they are the nearest vehicle to the geographical coordinates of any junction obtained from the integrated maps, which we proved to be the most suitable location to access new areas of the topology. This scheme also requires maintaining a neighbor list in each vehicle to determine the relative position of the surrounding vehicles.

NJL only focuses on the location of the receiving vehicle, ignoring the distance between sender and receiver. Figure 5.3 shows the working flowchart of NJL. Whenever a vehicle receives a warning message, it determines whether it is the nearest to any junction of the road layout by comparing its location to the locations of the neighbor vehicles. The scheme includes a security mechanism to avoid malfunction due to the radio interface or GPS errors, waiting for a rebroadcast backoff time before forwarding the message whenever a better positioned vehicle is expected (right side part of the flow chart).

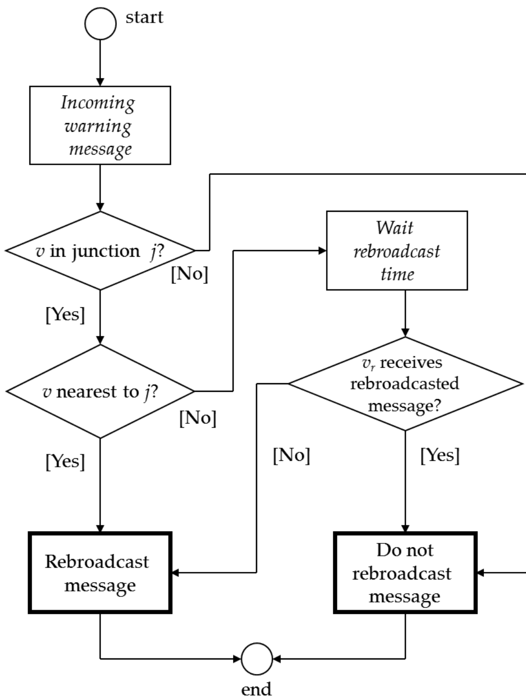



Figure 5.3: NJL dissemination scheme working flowchart.

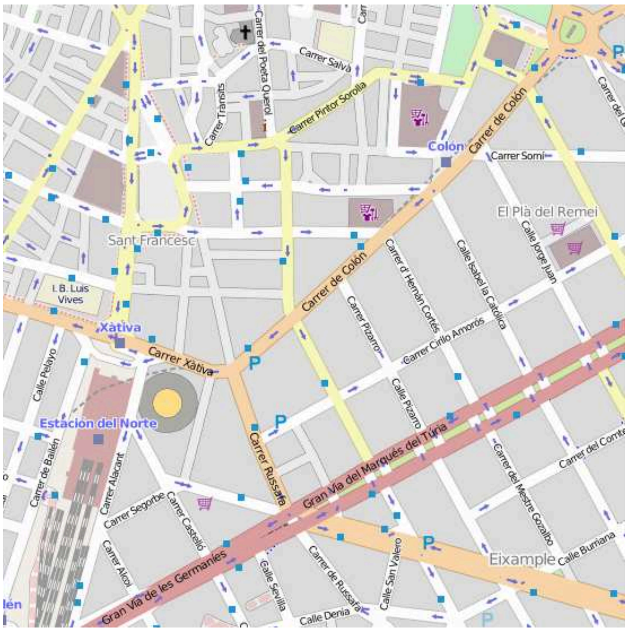
Although the performance of this approach is not optimal in sparse environments due to its restrictiveness, it performs efficiently in high density scenarios where the dominant factor to improve the dissemination process is the position of the vehicles.

## 5.4 Simulation Environment

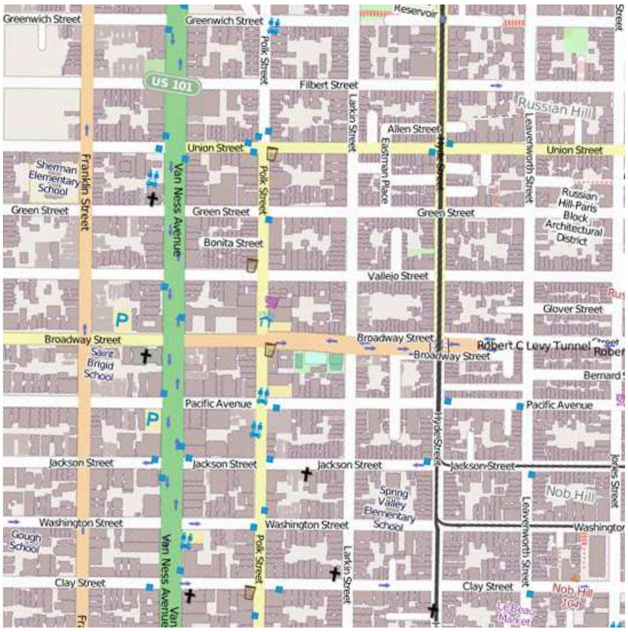
Simulation results presented in this chapter were obtained using the the simulation environment presented in Section 2.4.

Figure 5.4 shows the topology used in our simulations, obtained from the downtown areas of the cities of Valencia (Spain) and San Francisco (USA). The roadmaps used were selected in order to have different profile scenarios (i.e., with different topology characteristics). As shown in Figure 5.4 and according to [SFG$^+$13b], we consider Valencia as a complex topology city and San Francisco a simple topology city.

In our simulations, we included 1 warning mode vehicle in low density scenarios including 10, 20, and 30 vehicles/km$^2$, and 3 warning mode vehicles in high density scenarios accounting for 300, 400, and 500 vehicles/km$^2$. All the results represent an average of over 50 repetitions with different random scenarios, obtaining for all




(a)




(b)

Figure 5.4: Maps of: (a) Valencia and (b) San Francisco used in the simulations.

Table 5.3: Parameter settings in the simulations.

| **Parameter** | **Value** |
|---|---|
| roadmap | Valencia and San Francisco |
| number of vehicles per km$^2$ | $[10, 20, 30, 300, 400, \text{and } 500]$ |
| number of collided vehicles | 1 and 3 |
| roadmap size | $1000m \times 1000m$ |
| warning message size | $256B$ |
| beacon message size | $512B$ |
| warning messages priority | $AC3$ |
| beacon priority | $AC1$ |
| interval between messages | 1 second |
| MAC/PHY | 802.11p |
| radio propagation model | $RAV$ [MFT$^+$13] |
| mobility model | $Krauss$ [KWG97] |
| channel bandwidth | $6Mbps$ |
| max. transmission range | $400m$ |
| $d_{min}$ (used in distance-based, eSBR, and eMDR schemes) | $200m$ |

of them a confidence degree of 95%. Table 5.3 shows the main parameters used for the simulations.

We are interested in the following performance metrics presented in Section 2.4: (i) percentage of informed vehicles, (ii) number of messages received per vehicle, and (iii) warning notification time.

## 5.5 Simulation Results

It is necessary to assess the performance of the proposed schemes to prove their efficiency compared to existing mechanisms. From Section 5.2, we selected the counter-based, eSBR, flooding, NSF, and JSF schemes to compare them in those scenarios with very low densities, as well as the distance-based, eMDR, and NJL schemes to compare them in very high density scenarios.

### 5.5.1 Performance Evaluation in Low Vehicle Density Scenarios

Figures 5.5 and 5.6 show the simulation results obtained when simulating the maps of Valencia and San Francisco with three different low vehicle densities: 10, 20, and 30 vehicles/km$^2$.

The different schemes provide similar results during the first 20 seconds of the simulation in terms of informed vehicles. However, after the initial 20 seconds, the benefits of using a Store-and-Forward technique are especially noticeable. The JSF and NSF schemes inform more vehicles than the eSBR and the counter-based

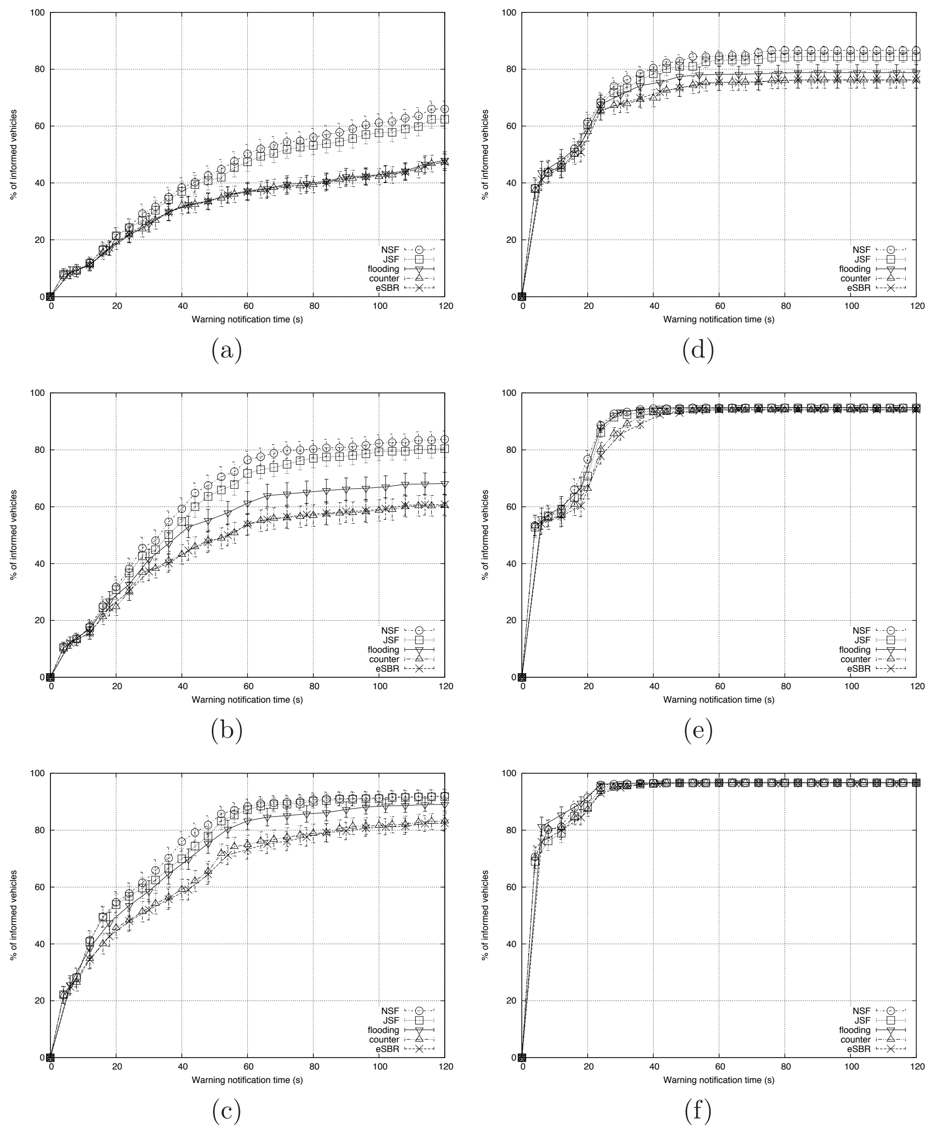
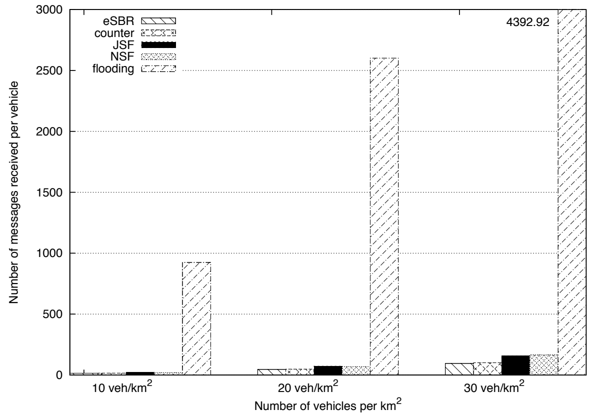
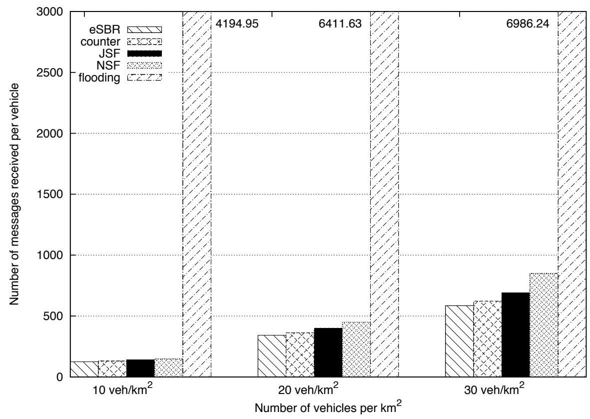



Figure 5.5: Percentage of informed vehicles in Valencia for: (a) 10, (b) 20, and (c) 30 vehicles/km2, as well as in San Francisco for: (d) 10, (e) 20, and (f) 30 vehicles/km$^2$.




(a)




(b)

Figure 5.6: Number of messages received per vehicle under low vehicle density conditions in: (a) Valencia and (b) San Francisco.

Table 5.4: Average time necessary to inform 60% of the vehicles

| Map | Density | NSF | JSF | Flooding | Counter | eSBR |
|---|---|---|---|---|---|---|
| Valencia | 10 veh./km$^2$ | 95 $s$ | 111 $s$ | - | - | - |
| | 20 veh./km$^2$ | 40 $s$ | 43 $s$ | 58 $s$ | 108 $s$ | 105 $s$ |
| | 30 veh./km$^2$ | 26 $s$ | 29 $s$ | 32 $s$ | 43 $s$ | 43 $s$ |
| San Francisco | 10 veh./km$^2$ | 19 $s$ | 19 $s$ | 20 $s$ | 20 $s$ | 20 $s$ |
| | 20 veh./km$^2$ | 13 $s$ | 14 $s$ | 13 $s$ | 14 $s$ | 17 $s$ |
| | 30 veh./km$^2$ | 2 $s$ | 2 $s$ | 2 $s$ | 2 $s$ | 2 $s$ |

schemes while producing a similar number of messages. As an example, JSF is able to notify 80% of vehicles in the Valencia scenario under 20 vehicles/km$^2$ after 120 seconds, whereas the eSBR and counter-based schemes only notify 60% of the vehicles during the same period, requiring only a slightly increase of the messages produced. The downside of the flooding scheme is that requires an enormous amount of messages to inform only 70% of vehicles in the same scenario.

Focusing on the number of messages, apart from the flooding approach, the differences are not significant due to the low chance of channel overload. However, the NSF scheme produces about 25% more messages under 30 vehicles/km$^2$ than the rest of schemes, achieving a slight performance gain on convergence speed compared to JSF. Even if it represents a noticeable increase in the required number of messages, the low vehicle density of the scenarios reduces the overall traffic in the wireless channel, and the effect on the performance is not remarkable. Note that the number of messages received per vehicle is higher in San Francisco, since its topology is simpler, and warning messages can reach the rest of vehicles easier.

Table 5.4 shows the average time required by the NSF, JSF, flooding, counter-based, and eSBR schemes to inform 60% of the vehicles in the scenario. As shown, the eSBR and counter-based schemes are about 150% slower when simulating Valencia under 20 vehicles/km$^2$, and about 50% slower when simulating 30 vehicles/km$^2$ compared to JSF, in spite of the low differences in terms of number of messages received per vehicle. Regarding more simple maps like San Francisco, there are not significant differences between the schemes, specially for 30 vehicles/km$^2$.

Finally, it is noticeable how our JSF and NSF proposed schemes are able to outperform the flooding scheme concerning percentage of informed vehicles, while drastically reducing the number of messages received per vehicle. Hence, using Store-and-Forward strategies and exploiting the topology of the roadmap allow achieving better performance compared to existing dissemination schemes, obtaining significant improvements with a reduced amount of additional messages.

### 5.5.2 Performance Evaluation in High Vehicle Density Scenarios

Figures 5.7 and 5.8 show the results obtained in Valencia and San Francisco when simulating very high vehicle densities, i.e., 300, 400, and 500 vehicles/km$^2$.

As shown, the distance-based scheme offers a poor performance in terms of per-

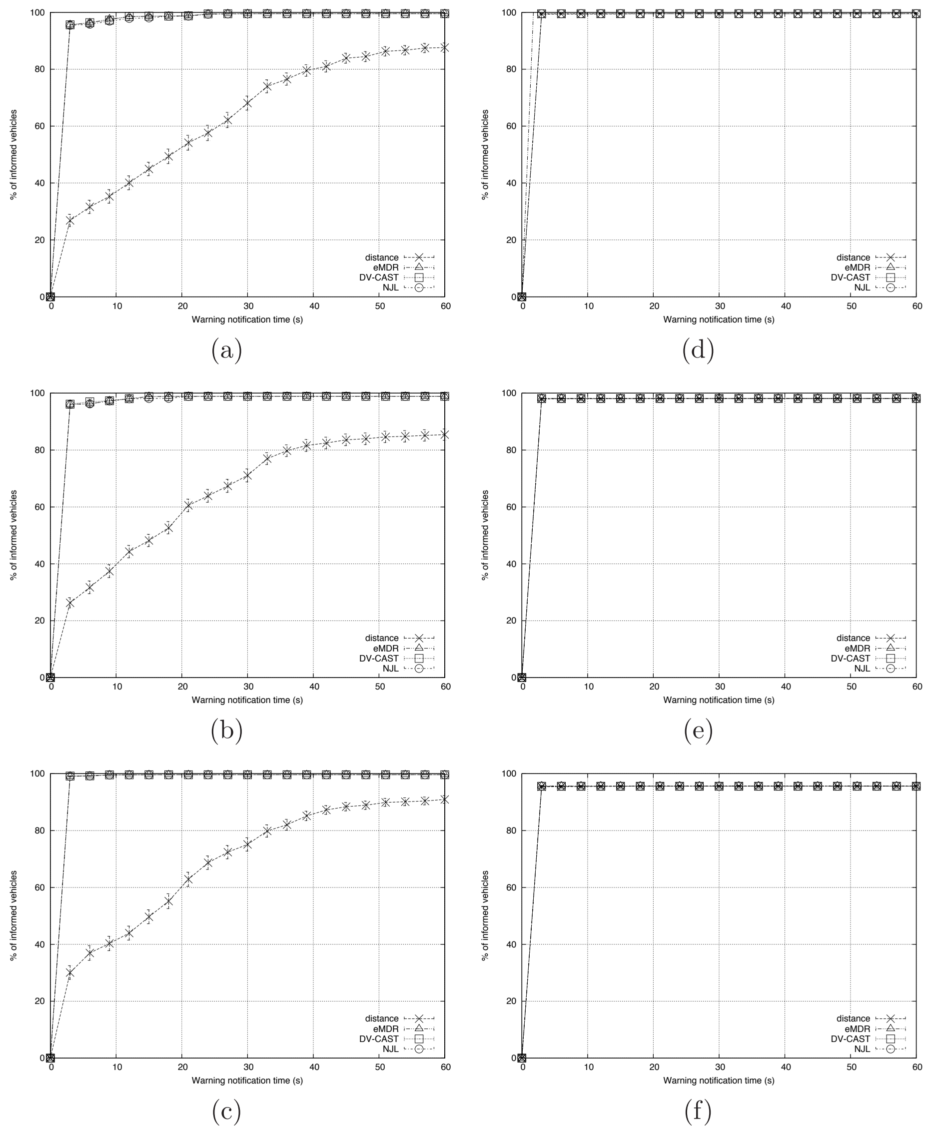



Figure 5.7: Percentage of informed vehicles in Valencia for: (a) 300, (b) 400, and (c) 500 vehicles/km$^2$, as well as in San Francisco for: (d) 300, (e) 400, and (f) 500 vehicles/km$^2$.

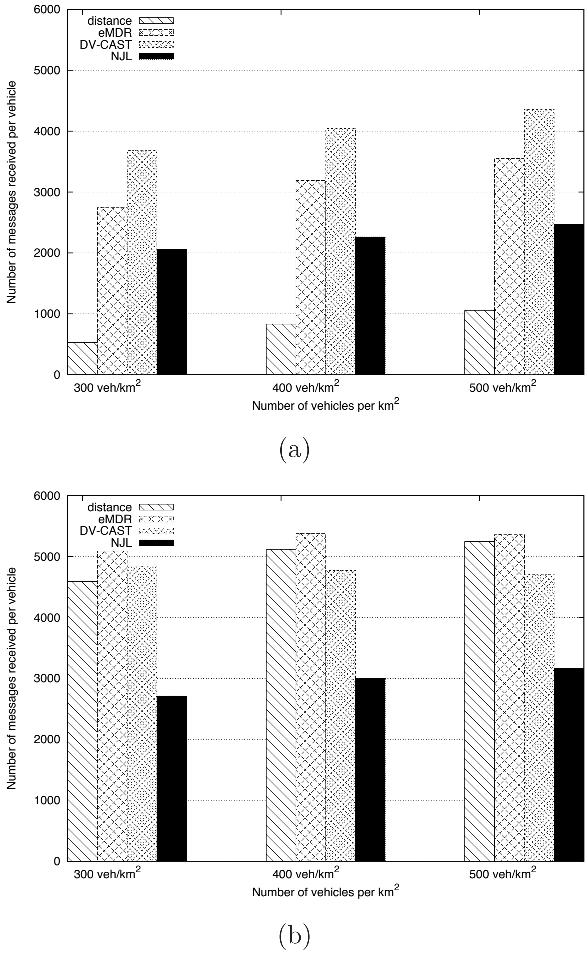



Figure 5.8: Number of messages received per vehicle under high vehicle density conditions in: (a) Valencia, and (b) San Francisco.

Table 5.5: Performance of the different dissemination schemes under high density conditions.

| | | Valencia | | | San Francisco | | |
|---|---|---|---|---|---|---|---|
| vehicles | Bcast | $P_{Inf}$ | $M_{recv}$ | efficiency | $P_{Inf}$ | $M_{recv}$ | efficiency |
| 300 | **distance** | 91.36% | 530.7 | 94.19 | 99.53% | 4589.98 | 53.88 |
| | **eMDR** | 99.56% | 2741.35 | 72.47 | 99.53% | 5093.06 | 48.83 |
| | **DV-CAST** | 99.56% | 3684.68 | 62.99 | 99.53% | 4845.73 | 51.31 |
| | **NJL** | 99.56% | 2060.03 | 79.31 | 99.53% | 2712.69 | 72.75 |
| 400 | **distance** | 89.17% | 831.37 | 90.68 | 98.13% | 5112.89 | 47.90 |
| | **eMDR** | 98.91% | 3188.47 | 67.76 | 98.13% | 5476.30 | 45.21 |
| | **DV-CAST** | 98.91% | 4041.61 | 59.14 | 98.13% | 4771.53 | 51.38 |
| | **NJL** | 98.91% | 2263.02 | 77.12 | 98.13% | 2998.38 | 69.45 |
| 500 | **distance** | 92.93% | 1050.21 | 88.70 | 95.57% | 5245.92 | 45.11 |
| | **eMDR** | 99.62% | 3551.35 | 64.35 | 95.57% | 5357.97 | 43.94 |
| | **DV-CAST** | 99.62% | 4357.68 | 56.26 | 95.57% | 4711.70 | 50.70 |
| | **NJL** | 99.62% | 2461.49 | 75.29 | 95.57% | 3164.20 | 66.89 |

centage of informed vehicles when compared to the NJL, DV-CAST, and eMDR dissemination schemes. Hence, it is not suitable for highly congested urban scenarios where warning message dissemination requires fast notification of dangerous situations. Note that the NJL, DV-CAST and eMDR schemes basically present the same results in terms of notification time and percentage of informed vehicles, whereas the number of messages received per vehicle when using the NJL scheme is reduced, ranging from 24.85% to 30.69% compared to eMDR, and from 43.51% to 44.09% compared to DV-CAST in Valencia, therefore making NJL the most suitable dissemination scheme in this kind of scenarios.

Regarding simple maps like San Francisco, since they have long and straight streets, channel contention and message collisions due to the higher number of vehicles in line-of-sight are prone to occur. In this kind of scenarios, NJL is again the scheme that provides the lower amount of messages, offering a reduction ranging from 40.94% to 46.73% compared to eMDR, from 32.84% to 44.01% compared to DV-CAST, and from 39.68% to 41.36% compared to the distance-based approach; the differences between the four schemes in terms of informed vehicles through time are null.

Since broadcast storms are prone to occur in high density situations due to serious redundancy, contention, and massive packet collisions caused by simultaneous forwarding, existing broadcast storm reduction techniques usually adopt very restrictive dissemination schemes that can compromise the reliability of the communication system.

Table 5.5 shows the simulation results of different schemes in high density environments in terms of percentage of informed vehicles, and the average messages received per vehicle after 120 seconds. Additionally, we added a new metric called "efficiency" which allows having an approximate idea about the number of messages required to inform 1% of vehicles (i.e., $100 - (M_{recv}/P_{inf})$). As shown, in simple maps such as San Francisco, all dissemination schemes achieve similar results in terms of informed vehicles; however, in terms of efficiency, NJL obtains better results, since it is able to reduce the number of messages needed to inform the same percentage of vehicles. As for complex maps, such as Valencia, where the number of junctions is higher and the street length is lower, although the distance-based scheme offers the best results in terms of efficiency, it is not able to achieve the same percentage of informed vehicles, making it unreliable in the warning dissemination context. Once the distance-based approach is discarded, NJL becomes the most highly efficient solution, reducing significantly the number of messages needed to inform the same percentage of vehicles.

Overall, and according to results obtained, the proposed NJL scheme is the most suitable dissemination mechanism to be used in both simple and complex maps under very high vehicle density environments, significantly reducing the number of messages required to inform the same percentage of vehicles compared to other schemes. NJL mitigates the broadcast storm problem without compromising the reliability of the system.

## 5.6 Summary

In this chapter we studied the performance of different warning message dissemination schemes for VANETs under situations classified as adverse due to the very low or very high density of vehicles in the scenario. The efficiency of warning message dissemination processes under these conditions is reduced as a result of frequent network partitioning under low densities, and high channel contention under high vehicle densities. We proposed three dissemination approaches specially designed for these situations: the *Junction Store and Forward* (JSF) and the *Neighbor Store and Forward* (NSF) schemes for very low vehicle densities, as well as the *Nearest Junction Located* (NJL) scheme for very high vehicle densities.

Simulation results showed that our proposed schemes outperform the existing dissemination algorithms in terms of informed vehicles through time and messages received per vehicle. Comparing its performance with the counter-based and eMDR schemes, JSF allowed reducing the warning notification time up to 40% in low density scenarios. Additionally, the NSF dissemination scheme was the most efficient in low density scenarios, even if the performance gain with respect to JSF is not remarkable and may vary depending on the features of the topology. We also observed how the number of junctions where vehicles are allowed forwarding in JSF affects its performance, being more effective when there is no upper limit to the number of allowed rebroadcasts. As for under high density conditions, our NJL proved to be the most efficient of the tested schemes, being able to inform almost the same percentage of vehicles than other existing approaches, while reducing the number of messages between 30% and 50% compared to them.

# Chapter 6

# Lessons Learned and Comparison of Existing Broadcast Dissemination Schemes

So far, several dissemination schemes have been proposed for being used in Vehicular Networks, but their evaluation was done under different conditions, and using different simulators, making it difficult to determine which is the most optimal dissemination scheme for each particular scenario. This chapter presents a comparative analysis of their performance by evaluating them under the same conditions, and focusing on the same metrics, thus providing researchers with a general overview of the benefits and drawbacks associated to each scheme.

## 6.1 Introduction

In this chapter we classify the most important broadcast dissemination schemes proposed for VANETs so far, including our proposed schemes. Specifically, we review 19 different dissemination schemes which have been proposed to improve the warning message dissemination process, while mitigating the broadcast storm problem.

Existing works usually assess their proposals in very specific scenarios, with different vehicles densities, and under a wide variety of simulation tools. Therefore, in this chapter we assess the performance of the most relevant existing broadcast dissemination schemes, evaluating them fairly, i.e., under the same conditions, network model, simulation tool, and using the same metrics.

We consider that evaluating the dissemination schemes under the same conditions could shed some light into the advantages and drawbacks of each solution, making it possible to determine which one is the most suitable scheme to be used in each particular scenario.

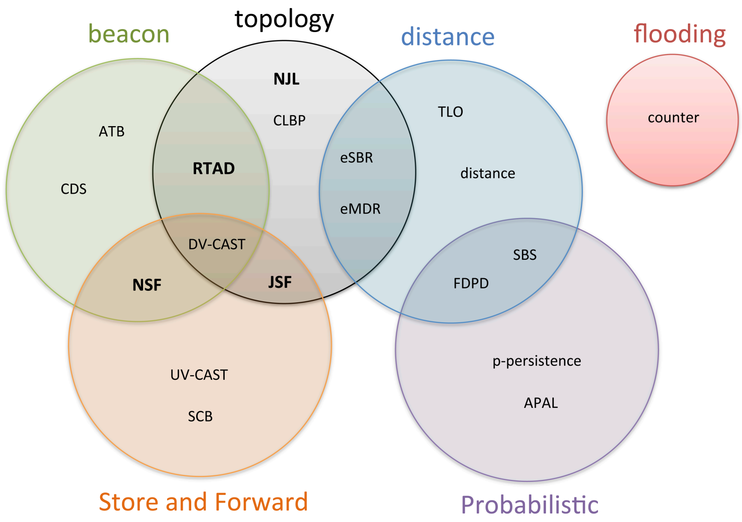



Figure 6.1: Venn diagram classifying the broadcast dissemination schemes studied according to the dissemination policy adopted including our proposed schemes.

The chapter is organized as follows: Section 6.2 proposes a classification of the existing proposals according to the characteristics and techniques adopted for the dissemination process. In Section 6.3 we present the variety of simulation configurations used to assess existing broadcast dissemination schemes. Section 6.4 shows the simulation environment we have selected to evaluate, under the same conditions, the performance of the different dissemination schemes studied. In Section 6.5, we present and discuss the obtained results, and, finally, Section 6.6 concludes this chapter.

## 6.2 Overall Classification of Warning Dissemination Messages Including our Proposed Schemes

Figure 6.1 shows the proposed classification of the broadcast dissemination schemes previously presented in Chapter 2. This figure also includes the broadcast dissemination schemes that we have proposed along this Thesis. As shown, the proposed schemes fill the gaps we detected before starting the work done during this work.

In particular, we proposed the NJL, a very restrictive dissemination scheme specially designed to reduce the broadcast storm problem, which accounts for the roadmap topology. This scheme reduces significantly the amount of messages received per vehicles in extremely high vehicle density scenarios, without any reduction of efficiency.

In order to improve the warning dissemination process in sparse environments, we used Store-and-Forward based techniques: on the one hand, we combined it with topology information in the design of JSF, which is especially effective in complex maps. On the other hand, we combined the Store-and-Forward based techniques with beaconing information to implement NSF, improving significantly the performance of all the schemes previously proposed.

Finally, we combined the topology and the beacon information, the most determinant features in the warning dissemination process, in order to design RTAD, our adaptive broadcast dissemination scheme.

## 6.3 Parameters Used to Assess the Performance of Existing Broadcast Dissemination Schemes

One of the challenges that researches should overcome when assessing their new proposals is to compare them against other similar previous approaches. However, it is difficult to determine which approaches present better performance, since those existing approaches usually have been validated under very different environments, and sometimes the simulation parameters are not very realistic, thus making the conclusions obtained inaccurate or unrepresentative. In this section, we discuss the different configurations used by researchers when evaluating their proposals.

Table 6.1 shows the parameters used by authors when assessing the performance of their proposed broadcast dissemination schemes (i.e., topology, radio propagation model, maximum transmission range, etc.). We consider that there are several important parameters that may affect the results obtained. However, we observed that the simulation environment and the parameters chosen greatly vary from one work to the other, making it difficult to determine which proposal is the most optimal. Next, we present the different parameters in detail.

Regarding topology, it is an important factor since it directly affects mobility and communication capabilities. In particular, the topology constrains vehicles' movements and it also affects wireless signal propagation (especially in urban environments and at high radio frequencies). Simulated road topologies can be generated ad hoc by users, randomly by applications, or obtained from real roadmap databases. As expected, using complex layouts implies more computational time, but the results obtained are closer to the real ones. However, 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 easy to implement in a simulator. However, layouts obtained from real urban scenarios should be chosen to ensure that the results obtained are likely to be similar in real environments.

As for the radio propagation model (RPM), we observe that the majority of proposals did not use RPMs offering enough accuracy for vehicular environments [MTC+09]. In particular, the physical obstacles present in urban environments (mostly buildings) are not usually taken into account, which is overly optimistic. For example, the commonly used Two Ray Ground (TRG) radio propagation model ignores effects such as Radio Frequency (RF) attenuation due to

Table 6.1: Parameters used in the simulations to evaluate the different broadcast schemes.

| **Scheme** | **Topology** | **RPM** | **Max. Tx** | **Standard** | **Mobility model** | **Simulator** |
|---|---|---|---|---|---|---|
| counter | 0.25-25 $km^2$ field | Free Space | 500 m | 801.11 | RWP | custom C++ |
| distance | 0.25-25 $km^2$ field | Free Space | 500 m | 801.11 | RWP | custom C++ |
| eSBR | 4 $km^2$ urban | RAV | 400 m | 802.11p | Krauss | ns-2 |
| eMDR | 4 $km^2$ urban | RAV | 400 m | 802.11p | Krauss | ns-2 |
| p-persistence | single and multi-lane | Free Space | 1000 m | 802.11a | - | OPNET |
| TLO | four lane street | - | 300 m | 802.11 | Uniform Speed | GrooveNET |
| APAL | four lane street | - | 200 m | 802.11b | Uniform Speed | GrooveNET |
| SBS | 1 $km^2$ field | - | 10 m | - | - | custom Java |
| CLBP | two line highway | TRG | 250 m | 802.11e | Constant Speed | ns-2 |
| NJL | 4 $km^2$ urban | RAV | 400 m | 802.11p | Krauss | ns-2 |
| RTAD | 4 $km^2$ urban | RAV | 400 m | 802.11p | Krauss | ns-2 |
| FDPD | 4 $km^2$ Manhattan | TRG | 200 m | 802.11 | Manhattan | J-Sim |
| UV-CAST | 1 $km^2$ urban | LOS | 140-250 m | 802.11p | CA-based | ns-2 |
| DV-CAST | circular highway | Ricean | - | 802.11a | Uniform Speed | ns-2 |
| NSF | 4 $km^2$ urban | RAV | 400 m | 802.11p | Krauss | ns-2 |
| JSF | 4 $km^2$ urban | RAV | 400 m | 802.11p | Krauss | ns-2 |

buildings and other obstacles, meaning that an alternative model should be used.

According to data presented in Table 6.1, we observe that different RPMs and maximum transmission ranges have been used when assessing the broadcast dissemination approaches:

- **Free Space model** [Fri46]. This model assumes ideal propagation conditions where there is only one clear line-of-sight path between the transmitter and the 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:

  $$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{6.1}$$

  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 $\lambda$ 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. However, the presence of obstacles such as building cannot be neglected in vehicular networks, especially in urban environments.

- **Two-Ray Ground Model (TRG)** [Rap01], this 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. However, similarly to the Free Space model, it ignores effects such as Radio Frequency (RF) attenuation due to buildings and other obstacles. Specifically, TRG estimates the received power at distance $d$ according to the following Equation 6.2:

  $$P_r(d) = \frac{P_t G_t G_r {h_t}^2 {h_r}^2}{d^4 L} \tag{6.2}$$

  where $h_t$ and $h_r$ are the heights of the transmit and receive antennas respectively. Note that the original equation [Rap01] assumes $L = 1$. To be consistent with the Free Space model, $L$ was added.

  The above equation shows a faster power loss than Equation 6.1 as distance increases. However, The TRG model does not provide accurate results for short distances due to the oscillation caused by the constructive and destructive combination of the two rays. Instead, the free space model is still commonly used when $d$ is small. Therefore, a cross-over distance $d_c$ is calculated in this model. When $d < d_c$, Equation 6.1 is used. When $d > d_c$, Equation 6.2 is used. At the cross-over distance, Equations 6.1 and 6.2 provide the same result, so $d_c$ can be calculated as follows:

  $$d_c = \frac{(4\pi h_t h_r)}{\lambda} \tag{6.3}$$

- **Line of Sight Dependant (LOS)** [VBT11]. This propagation model is based on the TRG. In particular, this model uses the TRG with a maximum transmission range of 250 m when sender and receiver are in line-of-sight (LOS), whereas it only considers a maximum transmission range of 140 m when an obstacle prevents the LOS.

- **Ricean Fading**. It is a stochastic model for the radio propagation anomalies caused by partial cancellation of a radio signal by itself; the signal arrives at the receiver through 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.

- **Real Attenuation and Visibility (RAV)** [MFT+13]. This model increases the level of realism in VANET simulations using real urban roadmaps, since it takes into account that the received signal will largely depend on both the distance between sender and receiver, and the presence of obstacles. RAV estimates if two vehicles can communicate according to real data obtained from experiments in the 5.9 GHz frequency band. In particular, this model estimates that communication is only possible when sender and receiver are in line-of-sight (LOS), with a maximum transmission range of 400 m.

Regarding the communication standard, the majority of proposals have been validated under the 802.11p standard, as expected. The purpose of the 802.11p standard is to provide the minimum set of specifications required to ensure interoperability between wireless devices when attempting to communicate in potentially fast-changing communication environments. In fact, the IEEE 802.11p it is expected to be widely adopted by the industry, hence new approaches related to vehicular networks should account for 802.11p specifications.

Another determinant factor in terms of performance and realism is the mobility model [AZ12], which provides an accurate and realistic vehicular mobility description at both macroscopic and microscopic levels [HFB09]. Based on previous studies addressing the mobility behavior of mobile users [Toh01], existing mobility models try to closely represent the movement patterns of drivers. These models provide a suitable environment for the simulation and evaluation of ad hoc communication performance.

To perform realistic vehicular simulations, and thus better assess new proposals, it is especially important to consider a detailed microscopic traffic simulation. Moreover, it is well known that mobility models can significantly affect simulation results.

According to data presented in Table 6.1, we observe that the following mobility models have been used:

- **The random waypoint model (RWP)** is by far the most popular mobility model [JLN03] in Mobile Ad hoc Networks (MANETs). However, in vehicular networks, 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 models designed for MANETs are usually not applicable to VANETs.

- **Constant speed** and **Uniform speed (USM)** models. A very simple mobility model is the Constant speed model, which considers that each vehicle moves at a constant speed $v$. The Uniform Speed Model allows vehicles to overtake other vehicles and increase their speed by a random value. This kind of models can be useful in highway scenarios, but they provide unrealistic results in urban scenarios.

- **The Manhattan model** [CBD02] is an stochastic model which uses a grid road topology, and 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.

- **The Krauss mobility model** [KWG97] is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)\tau}{\tau + 1} + \eta(t) \tag{6.4}$$

  where $v$ represents the speed of the vehicle in m/s, $t$ represents the period of time in seconds, $v_1$ is the speed of the leading vehicle in m/s, $g$ is the gap to the leading vehicle in meters, $\tau$ is the driver's reaction time (set to 1 second in our simulations) and $\eta$ is a random numeric variable with a value between 0 and 1. In our simulations we use the Krauss model and introduce some changes to provide multi-lane support [KHRW02].

- **The CA-based mobility model**. The cellular automata approach used to assess UV-CAST, was initially presented in [TVB09]. Despite its ease of implementation and simplicity, this model implements a realistic intersection control mechanism with traffic signal coordination, and it provides rules for realistic motion of turning vehicles. The CA model is capable of capturing and reproducing realistic features of traffic flow. In addition, due to its discrete nature, the CA model allows a very fast implementation and it can simulate a very large network at microscopical level in real time.

VANET simulations often involve large and heterogeneous scenarios. Compared to Mobile Ad Hoc Networks (MANETs), 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.

According to data presented in Table 6.1, we observe that the most widely used simulator is, by far, the ns-2 simulator [FV00], although other well-known simulators, such as OPNET [Riv13] and GrooveNet [Rea12], also receive much attention. The use of custom or ad hoc simulators is not a good idea, since results obtained may be unrepresentative, and, moreover, simulations should be easily reproduced by the researcher community.

Overall, we observe that some of the broadcast dissemination schemes proposed have been validated under different network simulators, which sometimes do not specifically address VANET scenarios and requirements. Additionally, some of the simulation environments used did not support IEEE 802.11p, obstacles, complex urban roadmaps, and vehicular traffic models. Hence, we consider to study their performance under a more realistic VANET simulation framework in order to correctly assess those proposals.

## 6.4 Simulation Environment

Simulation results presented in this chapter were obtained using the the simulation environment presented in Section 2.4.

Figure 6.2 shows the topologies used in our simulations, obtained from the downtown areas of Valencia (Spain) and San Francisco (USA). The roadmaps used in the simulations were selected in order to have different profile scenarios (i.e., with different topology characteristics). As shown in Figure 6.2, and according to [SFG+13b], we consider that Valencia has a complex topology, and that San Francisco has a simple topology.

Our mobility simulations account for areas with different vehicle densities since, in a real town, traffic is not uniformly distributed; instead, there are downtowns or points of interest that may attract vehicles, as well as points that repel vehicles (e.g., residential areas when people go to work).

All the results presented along this chapter represent an average of over 50 repetitions with different random scenarios, obtaining for all of them a confidence degree of 95%. Table 6.2 shows the main parameters used for the simulations. We are interested in the following performance metrics presented in Section 2.4: (i) percentage of informed vehicles, (ii) number of messages received per vehicle, and (iii) warning notification time.

## 6.5 Simulation Results

During the warning message dissemination process, the most important objective to accomplish consists on informing the highest number of vehicles in the shortest time possible without compromising the wireless channel. In this section we study the performance of some of the most relevant broadcast dissemination schemes proposed so far. Unlike previous works, we compare all of them under the same simulation conditions, thus making it possible to determine which are the optimal ones in each situation.

Figures 6.3 and 6.4 present the evolution of the dissemination process in terms of percentage of informed vehicles and warning notification time for the maps of


(a)


(b)

Figure 6.2: Maps of: (a) San Francisco, and (b) Valencia used in our simulations.

Table 6.2: Parameter settings in the simulations.

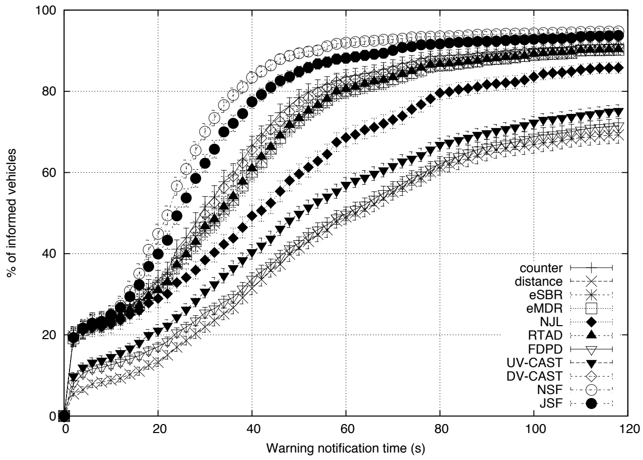
| **Parameter** | **Value** |
|---|---|
| roadmap | Valencia and San Francisco |
| number of vehicles per km$^2$ | [25 and 100] |
| number of collided vehicles | 3 |
| roadmap size | $2000m \times 2000m$ |
| warning message size | $256B$ |
| beacon message size | $512B$ |
| warning messages priority | $AC3$ |
| beacon priority | $AC1$ |
| interval between messages | 1 second |
| MAC/PHY | 802.11p |
| radio propagation model | $RAV$ [MFT$^+$13] |
| mobility model | $Krauss$ [KWG97] |
| channel bandwidth | $6Mbps$ |
| max. transmission range | $400m$ |
| $d_{min}$ (used in distance-based, eSBR, and eMDR schemes) | $200m$ |

San Francisco and Valencia when simulating two different vehicle densities (i.e., 25 and 100 vehicles/km$^2$).

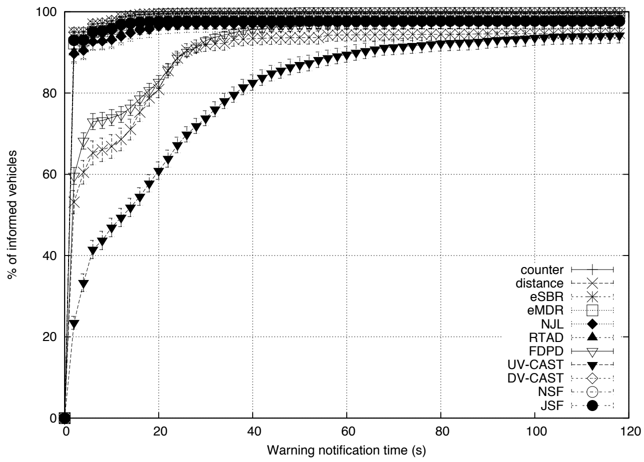
As shown, the NSF dissemination scheme achieves the highest percentage of informed vehicles in all cases, i.e., under both low and high vehicle density conditions, as well as under low and high topology complexity scenarios, obtaining up to 40% additional informed vehicles than more restrictive dissemination approaches, such as UV-CAST, FDPD, or distance-based dissemination schemes.

As for the number of messages received per vehicle (see Figures 6.5 and 6.6), it is directly related with the performance obtained in terms of informed nodes, i.e., a higher amount of messages received represents a better performance in terms of vehicles informed. However, under high densities and low complexity scenarios (see Figure 6.3b), we found that some dissemination schemes, such as RTAD, UV-CAST, eSBR, and eMDR, obtain results similar to NSF in terms of percentage of informed vehicles and warning notification time, while reducing to one fifth the number of messages received (as shown in Figure 6.5b).

Overall, it is noticeable how the roadmap topology and the vehicle density are determinant factors affecting the performance of the dissemination process. In general, the dissemination process develops faster (i.e., more vehicles are informed during a same period) when the vehicle density increases, independently from the broadcast scheme used, and especially under complex roadmaps. Store-and-Forward methods such as NSF and JSF offer the best results in terms of informed vehicles in all the studied situations, outperforming the other schemes; however, the number of messages also increases. This increment in terms of absolute number of messages is not significant at low densities, although it could be a problem in scenarios with extremely high vehicle densities. In addition, in simple roadmaps such us San Francisco, the differences between the majority of the schemes are

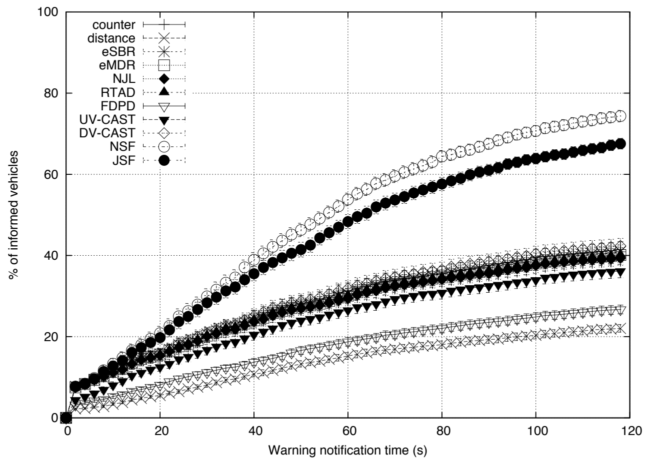



(a)

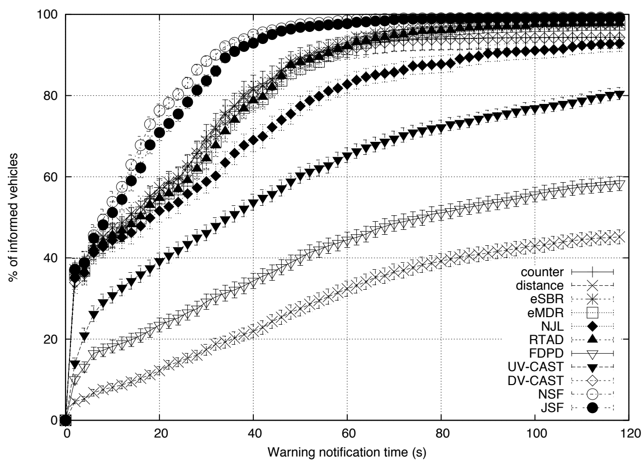



(b)

Figure 6.3: Percentage of informed vehicles and warning notification time in San Francisco for: (a) 25 and (b) 100 vehicles/km$^2$.

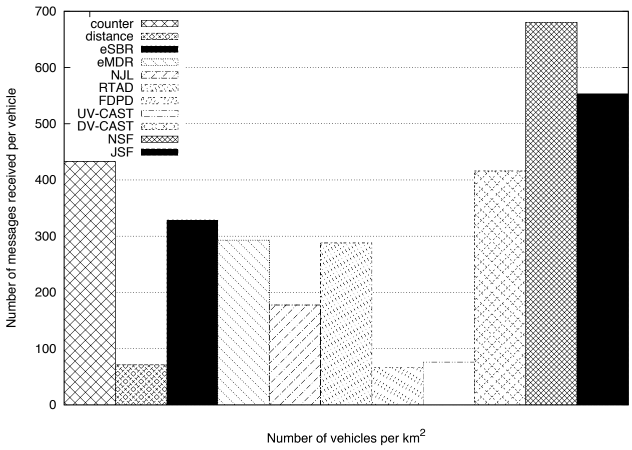



(a)

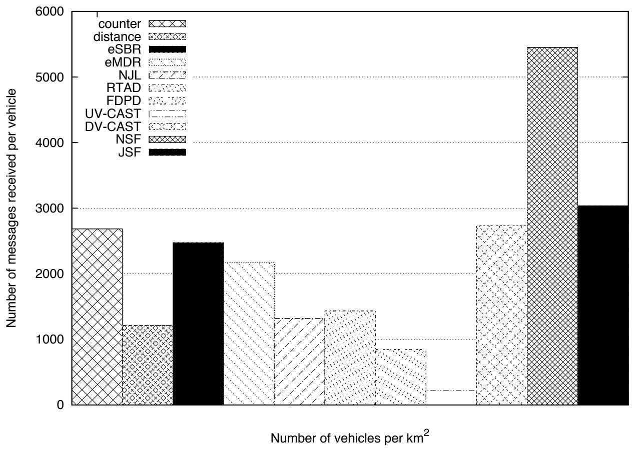



(b)

Figure 6.4: Percentage of informed vehicles and warning notification time in Valencia for: (a) 25 and (b) 100 vehicles/km$^2$.

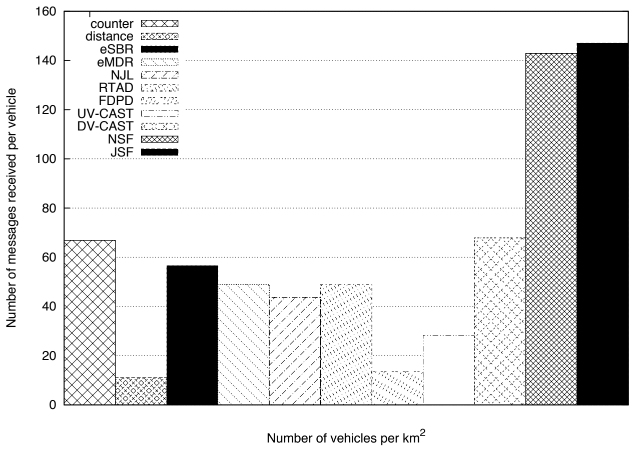



(a)

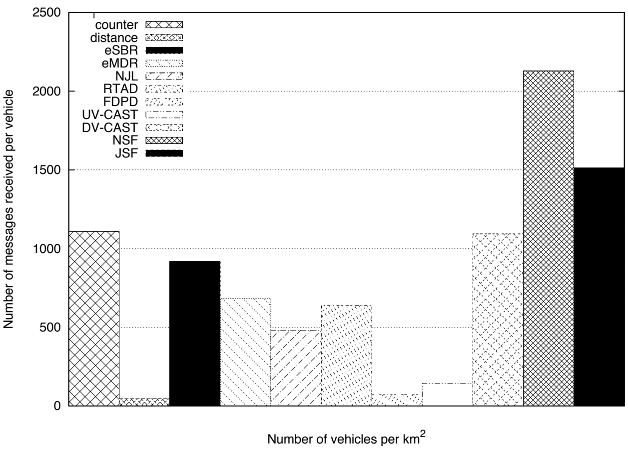



(b)

Figure 6.5: Number of messages received per vehicle in San Francisco for: (a) 25 and (b) 100 vehicles/km$^2$.




(a)




(b)

Figure 6.6: Number of messages received per vehicle in Valencia for: (a) 25 and (b) 100 vehicles/km$^2$.

minimal. Hence, it would be better to use dissemination schemes which produce a lower number of messages per vehicle.

## 6.6 Summary

In this chapter we presented some of the most relevant broadcast dissemination schemes specially designed for VANETs, highlighting their features, and studying their performance under the same simulation conditions, thus offering researchers a fair comparison between different broadcast schemes.

In particular, we presented a classification of the broadcast dissemination schemes, and classified them according to the different characteristics and techniques they use to determine whether a vehicle is allowed to rebroadcast a message. In addition, we simulated all these schemes by using a real visibility model, and under realistic urban environment conditions.

According to the results obtained, we observed that Store-and-Forward broadcasting schemes, which account for the beacons received and the topology of the maps where the vehicles are located, achieve better results in terms of percentage of informed nodes, especially in sparse scenarios. However, when density increases, the high volume of messages produced may saturate the channel. Additionally we find that, as expected, adaptive dissemination schemes (such as RTAD and DV-CAST) achieve intermediate values, offering a good trade off between the measured metrics (i.e., informed vehicles, warning notification time, and messages received) for all the vehicle densities studied.

# Chapter 7

# Conclusions, Publications, and Future Work

Current research on vehicular networks usually focuses on analyzing scenarios representing common situations with average and constant densities. However one of the main features on Vehicular Networks is the variability of the conditions. Our main objective was to design an adaptive broadcast scheme for warning message dissemination, in order to improve the performance of existing dissemination schemes, while addressing the broadcast storm problem.

Adaptive message dissemination schemes require to know important information about the context, such as the density of vehicles, the features of the roads, or the obstacles that could block the wireless signal. Therefore, one important issue to correctly disseminate warning messages in vehicular environments is to accurately estimate the current density of vehicles. Most of the existing vehicle density estimation techniques are designed for using infrastructure-based traffic information systems which require the deployment of this infrastructure and the economic cost associated. To address these limitations and problems, we proposed a function able to estimate the density in real time by each vehicle.

In addition, we studied adverse conditions in VANETs, since situations with very low or very high vehicle densities are often ignored, whereas they are very common in real vehicular environments. The goal of our proposed schemes is to maximize message delivery effectiveness, something difficult to achieve in adverse density scenarios.

We now proceed to summarize the most relevant contributions of this Thesis:

- Review of the most relevant existing broadcast dissemination schemes that are available in the recent literature, classifying them depending on the features used by the authors to determine their working mode.

- Proposal of a metric to measure the complexity of a roadmap scenario, namely SJ Ratio, which is calculated by dividing the number of streets between the number of junctions. Based on the obtained results, we consider that the cities which present a SJ Ratio greater than 1 have a complex topology, while the cities which present a lower than 1 SJ Ratio value have a simple topology.

- Design of an infrastructureless mechanism to estimate the vehicular density in urban environments. The mechanism uses as input parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located, allowing each vehicle to estimate the density of its neighborhood.
- Proposal of RTAD: a real-time adaptive dissemination system that allows each vehicle to automatically adopt the optimal dissemination scheme to adapt the warning message delivery policy to each specific situation. Our mechanism uses as input parameters the vehicular density and the topological characteristics of the environment where the vehicles are located, to decide which dissemination scheme to use at each moment.
- Proposal of both the *Junction Store and Forward* (JSF), and the *Neighbor Store and Forward* (NSF) dissemination schemes designed to be used under low density conditions, as well as the *Nearest Junction Located* (NJL) scheme specially developed for high density conditions. Simulation results showed that our proposed schemes outperform the existing dissemination algorithms in terms of informed vehicles through time and messages received per vehicle.
- Comparative analysis of the performance of all existing broadcast dissemination schemes, including our proposed ones, and evaluation of them under the same conditions and focusing on the same metrics, thus providing researchers with a general overview of the benefits and drawbacks associated to each scheme.

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.

## 7.1 Publications Related to the Thesis

The research work related to this Thesis has resulted in 11 publications; among them we have 4 journal articles (2 of them under review; all of them indexed by the Journal Citation Reports (JCR) database), 2 conference papers indexed by the Computer Science Conference Ranking or the Computing Research and Education (CORE) list, 3 International Conferences, and 2 National Conferences. We now proceed by presenting a brief description of each of them.

### 7.1.1 Journals

**[SFG+14c]** Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, and C. T. Calafate, "Using Topology and Neighbor Information to Overcome Adverse Vehicle Density Conditions", in *Transportation Research Part*

*C.* 2014. Available at: http://dx.doi.org/10.1016/j.trc.2014.02.010

Vehicular networks supporting cooperative driving on the road have attracted much attention due to the plethora of new possibilities they offer to modern Intelligent Transportation Systems. However, research works regarding vehicular networks usually obviate assessing their proposals in scenarios including adverse vehicle densities far from the average values, despite being common in real urban environments. In this paper, we study the effect of these hostile conditions on the performance of different schemes providing warning message dissemination. The goal of these schemes is to maximize message delivery effectiveness, something difficult to achieve in adverse density scenarios. In addition, we propose the *Neighbor Store and Forward* (NSF) scheme, designed to be used under low density conditions, and the *Nearest Junction Located* (NJL) scheme, specially developed for high density conditions. Simulation results demonstrate that our proposals are able to outperform existing warning message dissemination schemes in urban environments under adverse vehicle density conditions. In particular, NSF reduces the warning notification time in low vehicle density scenarios, while increasing up to 23.3% the percentage of informed vehicles. As for high vehicle density conditions, our NJL is able to inform the same percentage of vehicles than other existing approaches, while reducing the number of messages up to 46.73%.

The focus of Transportation Research Part C is high-quality, scholarly research that addresses development, applications, and implications, in the field of transportation, of emerging technologies from such fields as operations research, computer science, electronics, control systems, artificial intelligence, and telecommunications. For 2012, the journal TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES has an **Impact Factor of 2.006** and it is ranked in 7th place (of 30) of TRANSPORTATION SCIENCE & TECHNOLOGY category **(Q1)** of the JCR database.

**[SFG+13a]** Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "An Infrastructureless Approach to Estimate Vehicular Density in Urban Environments", in *Sensors* 2013, vol. 13, issue 2, pp. 2399-2418. Available at: http://dx.doi.org/10.3390/s130202399

In Vehicular Networks, communication success usually depends on the density of vehicles, since a higher density allows having shorter and more reliable wireless links. Thus, knowing the density of vehicles in a vehicular communications environment is important, as better opportunities for wireless communication can show up. However, vehicle density is highly variable in time and space. This paper deals with the importance of predicting the density of vehicles in vehicular environments to take decisions for enhancing the dissemination of warning messages between vehicles. We propose a novel mechanism to estimate the vehicular density in urban environments. Our mechanism uses as input parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located. Simulation results indicate that, unlike previous proposals solely based on the number of beacons received, our approach is able to accurately estimate the vehicular density, and therefore it could support more efficient dissemination protocols for vehicular environments, as well as improve previously proposed schemes.

Sensors is the leading international, peer-reviewed, open access journal on the science and technology of sensors and biosensors. For 2012, the journal SENSORS has an **Impact Factor of 1.953** and it is ranked in 8th place (of 57) of INSTRUMENTS & INSTRUMENTATION category **(Q1)**.

**[SFG+14b]** Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, and C. T. Calafate, "A Survey and Comparative Study of Broadcast Message Dissemination Schemes for VANETs", in *IEEE Communications Surveys and Tutorials*. 2014. *Under Review.*

Vehicular Ad hoc Networks (VANETs) enable cooperative driving between communicating vehicles on the road. In particular, they are forecasted as the adequate solution to increase traffic safety by providing useful traffic safety services. In this scope of application, vehicle-to-vehicle dissemination of warning messages to alert nearby vehicles is one of the most significant and representative solutions, whose main goal is to reduce the latency of such information while ensuring the correct reception of warning information in the vehicle's neighborhood as soon as a dangerous situation occurs. So far, several dissemination schemes have been proposed, but their evaluation was done under different conditions, and using different simulators, making it difficult to determine which is the most optimal dissemination scheme for each particular scenario. In this paper, we review the most relevant existing broadcast dissemination schemes available in the recent literature. Additionally, we provide a comparative analysis of their performance by evaluating them under the same conditions, and focusing on the same metrics, thus providing researchers with a general overview of the benefits and drawbacks associated to each scheme.

The IEEE Communications Surveys & Tutorials is a free online journal published by the IEEE Communications Society for tutorials and surveys covering all aspects of the communications field. For 2012, the journal IEEE COMMUNICATIONS SURVEYS & TUTORIALS has an **Impact Factor of 4.818** and it is ranked in 1st place (of 78) TELECOMMUNICATIONS category **(Q1)**.

[**SFG**$^+$**14a**] Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, and C. T. Calafate, "RTAD: a Real-time Adaptive Dissemination System for VANETs", in *Computer Communications*. 2014. *Under Review*.

Efficient message dissemination is of utmost importance to propel the development of useful services and applications in Vehicular ad hoc Networks (VANETs). In this paper, we propose a novel adaptive system that allows each vehicle to automatically adopt the optimal dissemination scheme in order to fit the warning message delivery policy to each specific situation. Our mechanism uses as input parameters the vehicular density and the topological characteristics of the environment where the vehicles are located, in order to decide which dissemination scheme to use. We compare our proposal with respect to two static dissemination schemes (eMDR and NJL), and three adaptive dissemination systems (UV-CAST, FDPD, and DV-CAST). Simulation results demonstrate that our approach significantly improves upon these solutions, being able to support more efficient warning message dissemination in all situations ranging from low densities with complex maps, to high densities in simple scenarios. In particular, RTAD improves existing approaches in terms of percentage of vehicles informed, while significantly reducing the number of messages sent, thus mitigating broadcast storms.

Computer Communications is a peer-reviewed international journal that publishes high-quality scientific articles (both theory and practice) and survey papers covering all aspects of future computer communication networks (on all layers, except the physical layer), with a special attention to the evolution of the Internet architecture, protocols, services, and applications. For 2012, the journal COMPUTER COMMUNICATIONS has an **Impact Factor of 1.079** and it is ranked in 35th place (of 78) of TELECOMMUNICATIONS category **(Q2)**.

### 7.1.2 Indexed Conferences

[**SFG**$^+$**13b**] Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "On the Selection of Optimal Broadcast Schemes in VANETs", in *16th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, Barcelona, Spain, pp. 411-418, November 2013.
Available at: http://dx.doi.org/10.1145/2507924.2507935

In Vehicular ad hoc Networks (VANETs), efficient dissemination of messages is a key factor to speed up the development of useful services and applications. In this paper, we propose a novel algorithm that automatically chooses the best dissemination scheme trying to fit the warning message delivery policy to the current characteristics of each specific vehicular scenario. Our mechanism uses as input parameters the vehicular density and the topological characteristics of the environment where the vehicles are located, in order to decide which dissemination scheme to use. Simulation results demonstrate the feasibility of our approach, which is able to support more efficient warning message dissemination in vehicular environments.

ACM MSWiM 2013 is the 16th Annual International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. MSWiM is an international forum dedicated to in-depth discussion of Wireless and Mobile systems, networks, algorithms and applications, with an emphasis on rigorous performance evaluation. In 2013, the call for papers attracted 184 registered papers in all areas of mobile and wireless systems of which **160** were accepted into the review process. In the end, they selected **42** regular papers, which represents an acceptance rate of **26%**. MSWiM is **ranked with "A"** by The Computing Research and Education Association of Australasia (CORE).

[**SFG+14e**] Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, and C. T. Calafate, "Topology-based Broadcast Schemes for Urban Scenarios Targeting Adverse Density Conditions", in *IEEE Wireless Communications and Networking Conference (WCNC)*, Istanbul, Turkey, April 2014.

Research works regarding vehicular communications usually obviate assessing the proposals in scenarios including adverse vehicle densities, despite such scenarios are quite common in real urban environments. In this paper, we study the effect of these hostile conditions on the performance of different schemes providing warning message dissemination. We then propose the *Junction Store and Forward* (JSF) and the *Nearest Junction Located* (NJL) schemes, which were specially designed to be used in very low and very high density scenarios, respectively. Simulation results using real maps demonstrate how our proposed schemes are able to outperform existing warning message dissemination schemes in urban environments under adverse vehicle density conditions.

WCNC is the world premier wireless event that brings together industry professionals, academics, and individuals from government agencies and other institutions to exchange information and ideas on the advancement of wireless communications and networking technology. A total of 1,305 papers were submitted to IEEE WCNC 2014. **606** of the submitted papers were accepted; this results in an acceptance ratio of **46%**. WCNC is **ranked with "B"** by The Computing Research and Education Association of Australasia (CORE).

### 7.1.3 International Conferences

[**SFG+12b**] Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Real-Time Density Estimation in Urban Environments by using Vehicular Communications", in *5th IFIP Wireless Days Conference*, Dublin, Ireland, pp. 1-6, November 2012.
Available at: http://dx.doi.org/10.1109/WD.2012.6402835

Knowing the density of vehicles in a vehicular communications environment is important, as better opportunities for wireless communication can show up. This paper studies the importance of predicting the density of vehicles in vehicular environments to take decisions for enhancing the dissemination of warning messages between vehicles. Moreover, we propose a mechanism which allows the estimation of the vehicular density within a certain urban environment, using as parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located.

The Wireless Days Conference is a major international conference which aims to bring together researchers, technologists and visionaries from academia, research centers and industry, engineers and students to exchange, discuss, and share their experiences, ideas and research results about theoretical and practical aspects of wireless networking. In 2012, they received more than **158** papers from 45 different countries worldwide. They selected the top **34.81%** papers for presentation in the conference.

**[BSF+13]** Javier Barrachina, Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "V2X-d: a Vehicular Density Estimation System that combines V2V and V2I Communications", in *6th IFIP Wireless Days Conference*, Valencia, Spain, pp. 1-6, November 2013.
Available at: http://dx.doi.org/10.1109/WD.2013.6686518

Road traffic is experiencing a drastic increase, and vehicular traffic congestion is becoming a major problem, especially in metropolitan environments throughout the world. Additionally, in modern Intelligent Transportation Systems (ITS) communications, the high amount of information that can be generated and processed by vehicles will significantly increase message redundancy, channel contention, and message collisions, thus reducing the efficiency of message dissemination processes. In this work, we present a V2X architecture to estimate traffic density on the road that relies on the advantages of combining V2V and V2I communications. Our proposal uses both the number of beacons received per vehicle (V2V) and per RSU (V2I), as well as the roadmap topology features to estimate the vehicle density. By using our approach, modern Intelligent Transportation Systems will be able to reduce traffic congestion and also to adopt more efficient message dissemination protocols.

The WD'13 Technical Program Committee received 184 technical paper submissions from 30 different countries. From these **184** submissions, **63** full papers were selected for presentation at the 2013 edition in Valencia. The overall **acceptance ratio was 34.24%**.

Since our work received one of the best evaluations in the review process, we were invited to extend our work to be published in a special issue of the ANNALS OF TELECOMMUNICATIONS JOURNAL (Springer). This journal is indexed by the JCR database.

**[SFG+14d]** Julio A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, and C. T. Calafate, "Broadcast Message Dissemination Schemes for Urban

Environments: a Survey", in *2014 The International Industrial Information Systems Conference*, Chiang Mai, Thailand, pp. 125-129. January 2014. ISSN 2287-6862.

In VANET traffic safety applications, efficient warning message dissemination is required. The main goal is to reduce the latency while ensuring the correct reception of warning information by nearby vehicles when a dangerous situation occurs. So far, several dissemination schemes have been proposed and evaluated under different conditions, and using different simulators, making it difficult to determine which is the optimal dissemination scheme. In this paper, we assess the performance of several existing broadcast dissemination schemes by evaluating them under the same conditions, and focusing on the same metrics, thus providing researchers with a general overview of the drawbacks and benefits associated to each scheme.

The International Industrial and Information Systems Conference (IIISC 2014) is one of the world's premier networking forums of leading researchers in the highly active fields of industrial information systems. At IIISC 2014, IT experts, researchers, and practitioners from each field were invited to share ideas and research technologies; moreover, encouraged to cooperate with each other to overcome the confronted technical problems.

### 7.1.4 National Conferences

**[SFG+12a]** J. A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Estimación en tiempo real de la densidad de vehículos en entornos urbanos", in *XXIII Jornadas de Paralelismo*, Elche, Spain, pp. 127-132, September 2012.

In vehicular networks, communication success usually depends on the density of vehicles, as a higher density allows having shorter and more reliable wireless links. However, vehicle density is highly variable in time and space. Thus, knowing the density of vehicles in a vehicular communications environment is important, as better opportunities for wireless communication can show up. This paper studies the importance of predicting the density of vehicles in vehicular environments to take decisions for enhancing the dissemination of warning messages between vehicles. Moreover, we propose a mechanism which allows the estimation of the vehicular density within a certain urban environment, using as parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located. Simulation results indicate that our approach accurately estimates the vehicular density, and therefore it may be used by researchers in order to design adaptive dissemination protocols for vehicular environments, or to improve previously proposed schemes.

Jornadas de Paralelismo is a scientific-technical nationally conference celebrated annually since 1990. The basic objective of this conference is to bring together Spanish researchers in order to exchange their experiences, to present and discuss research results, to promote coordination between

Spanish groups, and to share their ideas on trends related with parallelism, architecture and computers networks.

**[SFG+13c]** J. A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Broadcast Schemes for Disseminating Safety Messages in VANETs", in *XXIV Jornadas de Paralelismo*, Madrid, Spain, pp. 298-303, September 2013.

In Vehicular ad hoc Networks (VANETs), the efficient dissemination of messages is a key factor to speed up the development of useful services and applications. In this paper, we present the Optimal Broadcast Selection algorithm, a novel proposal that automatically chooses the best broadcast scheme trying to fit the warning message delivery policy to the current characteristics of each specific vehicular scenario. Our mechanism uses as input parameters the vehicular density and the topological characteristics of the environment where the vehicles are located, in order to decide which dissemination scheme to use. Simulation results demonstrate the feasibility of our approach, which is able to support more efficient warning message dissemination in vehicular environments.

## 7.2 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 a full RTAD algorithm. RTAD scheme is designed to offer the suitable scheme in each usual situation, however, extreme situations such as very high or very low densities can appear in vehicular environments. Adding extreme broadcast dissemination schemes in RTAD would address this problem.

- To study message dissemination when varying the vehicle density along simulation time. We consider that adaptive dissemination approaches such as RTAD should obtain better results than static dissemination systems in scenarios with variable vehicle density, since they would adapt their dissemination policy to fit these adverse environmental conditions.

- To develop a full system which uses V2V and V2I communications. The combination of both communication approaches would offer several advantages. For example, V2V would offer V2I a tolerance error system, in terms of measuring the density when a RSU fails, in addition, V2I could offer additional services such as network connection to V2V vehicles.

- Along this Thesis we used number of vehicles per $km^2$ in order to measure the vehicle density. However, this metric could lead to wrong or inaccurate conclusions, due to the special characteristics of roadmap layouts. In this Thesis we have proved the importance of the topology in the warning message dissemination process, so we consider that the vehicle density metric should be further studied.

- Finally, we would like to implement all our proposals in a real testbed. Since simulation results obtained are very promising, we consider that a real implementation should confirm the feasibility and potential of our adaptive broadcast dissemination mechanism and the rest of proposals made in this Thesis.

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