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Connectivity-based Routing and Dissemination Protocols for Vehicular Networks

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INFORMA

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Abstract

Cooperative Intelligent Transport Systems (ITS) are expected to improve road traffic safety and efficiency through the dynamic exchange of wireless messages between vehicles (Vehicle-to-Vehicle, V2V), and with infrastructure nodes (Vehicle-to-Infrastructure, V2I). Cooperative ITS applications will exploit this exchange of messages to extend, in time and space, the drivers' awareness and capability to detect dangerous or problematic road traffic situations. To address the requirements of cooperative ITS applications and the challenging characteristics of vehicular communications, the IEEE 802.11p and ETSI ITS G5 standards are being specified. These standards permit direct and multi-hop V2V and V2I communications. Multi-hop communications over vehicular networks enable the transmission of messages to distant nodes, and the distribution of information to vehicles over relevance areas. However, these capabilities strongly depend on the design and implementation of efficient and effective vehicular routing and dissemination protocols. These protocols need to be able to overcome the challenging characteristics of vehicular environments (vehicular mobility, varying propagation conditions and vehicular density, and scarce communication resources). In this context, this thesis presents and evaluates novel vehicular routing and dissemination protocols based on the concept of "*multi-hop road connectivity*". Multi-hop road connectivity is defined as the capability of a road segment to support multi-hop transmissions along its length. A distributed mechanism for real time multi-hop road connectivity estimation is proposed in the thesis. Compared to other approaches that try to infer the forwarding capability of road segments from vehicular density estimates, the proposed mechanism reduces the communications overhead. The thesis proposes then a GeoRouting protocol that uses multi-hop road connectivity estimates and contention-based broadcast transmissions. The contention-based approach increases the reliability of message forwarding. The use of real time multi-hop road connectivity estimates facilitates the adaptation of routing decisions to connectivity variations in vehicular networks. In addition, it results in a better distribution of the communications load in the routing scenario, and thereby in a lower spatial probability of channel congestion. Finally, the thesis proposes a hybrid dissemination protocol that exploits the advantages offered by heterogeneous wireless technologies. In particular, the proposed scheme combines cellular and multi-hop ad-hoc vehicular communications to disseminate information from

a centralized provider to the vehicles on a relevance area. Multi-hop road connectivity estimates are collected through the cellular network, and subsequently processed and fused to achieve a centralized picture of the vehicular network's connectivity context. The achieved context awareness guides a V2X dissemination process combining cellular information injections with a cooperative V2V dissemination. The context information permits performing smart injection strategies that increase the dissemination delivery capability without requiring a significant amount of cellular resources. The context awareness based on multi-hop road connectivity information is obtained with a low overhead on both cellular and vehicular ad-hoc networks. The effectiveness and efficiency of all the proposed protocols have been validated through computer simulations able to perform accurate, large scale, and communications standard compliant evaluations in a very modular way. In this context, this thesis also presents a novel cooperative ITS simulation platform that offers all these capabilities in a unique solution.

Resumen

Los sistemas inteligentes de transporte cooperativos (*Cooperative Intelligent Transport Systems*) han sido identificados como un medio prometedor para mejorar la seguridad vial y la eficiencia del tráfico. Estos sistemas se basan en el intercambio dinámico de mensajes entre vehículos (*Vehicle-to-Vehicle*, V2V), y entre vehículos y nodos de infraestructura (*Vehicle-to-Infrastructure*, V2I). Gracias a este intercambio de información, las aplicaciones cooperativas permitirán que un conductor pueda detectar situaciones de tráfico adversas o peligrosas con suficiente antelación, tanto en el tiempo como en el espacio. Para hacer frente a los estrictos requisitos de las aplicaciones cooperativas y a las condiciones adversas en las que se realizan las comunicaciones vehiculares, están siendo especificados los estándares de comunicación internacionales IEEE 802.11p y ETSI ITS G5. Estos estándares permiten realizar comunicaciones V2V y V2I directas o del tipo *multi-hop.* Las comunicaciones *multi-hop* en redes de comunicaciones vehiculares posibilitan la transmisión de mensajes hacia nodos lejanos y la distribución de información a vehículos situados en áreas de relevancia, empleando nodos intermedios como retransmisores. Sin embargo, el rendimiento de sistemas que emplean comunicaciones *multi-hop* depende ampliamente del diseño e implementación de protocolos de enrutamiento y diseminación eficaces y efectivos. Estos protocolos deben enfrentarse a los retos impuestos por el entorno de comunicación vehicular (la elevada movilidad de los vehículos, las condiciones variables de propagación radio y de densidad vehicular, y las escasez de recursos radio). En este contexto, esta tesis doctoral presenta y evalúa novedosos protocolos de enrutamiento y diseminación basados en el concepto de conectividad *multi-hop* de las calles o "*multi-hop road connectivity*". La conectividad *multi-hop* se define como la capacidad que presenta una calle para posibilitar comunicaciones *multi-hop*. En la tesis, se propone un mecanismo de comunicación para estimar esta conectividad *multi-hop* en tiempo real y de forma distribuida. Comparado con otros mecanismos que intentan extrapolar la capacidad de retransmisión *multi-hop* de una calle basándose en evaluaciones de su densidad de vehículos, el mecanismo propuesto genera menores niveles de sobrecarga en el canal radio. Utilizando el mecanismo de estimación de la conectividad *multi-hop* propuesto, se presenta un protocolo de enrutamiento que emplea retransmisiones *broadcast* basadas en contención. Este enfoque basado en contención proporciona robustez al proceso de

retransmisión de mensajes. Las estimaciones de la conectividad *multi-hop* permiten que las decisiones de enrutamiento se adapten dinámicamente a las variaciones de conectividad de la red vehicular. Además, el uso de estas estimaciones hace que la carga de comunicaciones se distribuya más uniformemente en el escenario, permitiendo de esta manera que se reduzca la probabilidad espacial de congestión del canal radio. Finalmente, la tesis propone un protocolo de diseminación híbrido que utiliza las ventajas de las comunicaciones radio heterogéneas. En particular, el protocolo propuesto combina comunicaciones celulares y comunicaciones V2V para diseminar información desde un proveedor centralizado hacia los vehículos situados en un área de relevancia. En particular, las estimaciones de la conectividad *multi-hop* se envían al proveedor centralizado utilizando la red celular, y los datos se procesan y fusionan para obtener una imagen global de la conectividad de la red vehicular. Este conocimiento contextual de la conectividad se emplea por el proceso de diseminación propuesto que combina inyecciones de la información mediante transmisiones celulares con una diseminación cooperativa en la red de vehículos a través de comunicaciones V2V. La información contextual permite realizar estrategias de inyección inteligentes que aumentan la fiabilidad del proceso de diseminación sin exigir una alta cantidad de recursos celulares. El conocimiento contextual de la conectividad basado en la información de conectividad *multi-hop* se obtiene con bajos niveles de sobrecarga de comunicaciones tanto en la red celular como en la vehicular. La eficacia y la eficiencia de todos los protocolos propuestos han sido validadas mediante simulaciones a gran escala con precisión, y conformes con los estándares de comunicación vehiculares. En este contexto, la tesis presenta una novedosa plataforma modular para la simulación de aplicaciones ITS cooperativas que ofrece estas capacidades en una única solución.

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List of Publications

To date, the work reported in this thesis has produced the following publications.

Publications on international journals with impact factor:

- M. Rondinone and J. Gozalvez, *"Contention-based Forwarding with Multi-hop Connectivity Awareness in Vehicular Ad-hoc Networks"*, Elsevier Computer Networks, Vol. 57, n. 8, pp. 1821-1837, June 2013
- M. Rondinone et al., *"iTETRIS: a modular simulation platform for the large scale evaluation of cooperative ITS applications"*, Elsevier Simulation Modelling Practice and Theory, Vol. 34, pp. 99-125, May 2013

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- M. Rondinone, J. Gozalvez, J. Leguay, and V. Conan, *"Exploiting Context Information for V2X Dissemination in Vehicular Networks"*, Proceedings of the 14th IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM 2013), Madrid (Spain), June 2013
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- J. Maneros, R. Bauzá, M. Rondinone, J. Gozalvez, O. Lázaro, A. González, *"Plataforma Modular para la Integración de Herramientas de Simulación de Comunicaciones Inalámbricas y Movilidad Urbana en la Evaluación de Sistemas Cooperativos a Gran Escala"*, Proceedings of X Congreso Español ITS, Madrid (Spain), May 2010

List of Acronyms

AC	Access Category
ACK	Acknowledgment
AP	Acknowledged vehicle Position
API	Application Program Interface
AWGN	Additional White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSA	Basic Set of Applications
BTP	Basic Transport Protocol
C2C	Car-to-Car
CALM	Communications Access for Land Mobiles
CAM	Cooperative Awareness Message
CBF	Contention Based Forwarding
CC	Control Channel
CDF	Cumulative Distribution Function
CDP	Cell Density Packet
CET	Connectivity Expiry Time
CF	Connectivity Field
CIU	Communication Infrastructure Unit
CL	Coverage Level
CS	Connectivity Stability
CSI	Connected Set of Intersections
CSV	Connected Set of Vehicles
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
DCF	Distributed Coordination Function
DCU	DiRCoD Connectivity Update
DENM	Decentralized Environmental Notification Message
DIFS	Distributed Inter-Frame Space

DiRCoD	Distributed and Real time communications Connectivity Discovery
DSRC	Dedicated Short Range Communications
EDCA	Enhanced Distributed Channel Access
EIRP	Equivalent Isotropically Radiated Power
eTOPOCBF	Efficient TOPOCBF
ETSI	European Telecommunications Standards Institute
EU	European Union
FOTs	Field Operational Tests
FP7	Seventh Framework Programme
FP	Fast Probing
FPRCC	Fast Probing Road Connectivity Characterization
GPS	Global Positioning System
GUI	Graphical User Interface
GyTAR	Improved Greedy Traffic-Aware Routing
HL	Hop Limit
I2V	Infrastructure-to-Vehicle
IAM	Injection Announcement Message
iAPP	iTETRIS implementation of a cooperative ITS APPlication
IB	Intersection-Based
IBSS	Independent BSS
IBRCC	Intersection-Based Road Connectivity Characterization
iCS	iTETRIS Control System
IEEE	Institute of Electrical and Electronics Engineers
IFTIS	Infrastructure-Free Traffic Information System
iNCI	iTETRIS Network simulator Control Interface
IP	Internet Protocol
ISO	International Organization for Standardization
iTETRIS	Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions
ITS	Intelligent Transport System
LDM	Local Dynamic Map
LOS	Line-of-Sight
LOS	Level of Service
LPV	Local Position Vector
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MBMS	Multimedia Broadcast Multicast Service

MW	Middleware
NIF	Next Intersection Field
NLOS	Non-Line-of-Sight
OFDM	Orthogonal Frequency Division Modulation
OSI	Open System Interconnection
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PIF	Previous Intersection Field
PRACH	Physical RACH
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RLC	Radio Link Control
RoAHD	Road Connectivity-Aware Hybrid V2X Dissemination
RSU	Road Side Unit
SC	Service Channel
SINR	Signal to Interference and Noise Ratio
SN	Sequence Number
TMC	Traffic Management Centre
TOPOCBB	Road Topology-Aware Contention-Based Broadcasting
TOPOCBF	Road Topology-Aware Contention-Based Forwarding
TraCI	Traffic Control Interface
UE	User Equipments
UF	Uploading Field
UMTS	Universal Mobile Telecommunications System
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Vehicle and to-Infrastructure
VANET	Vehicular Ad-hoc Network
VD	Virtual Distance
WAVE	Wireless Access to Vehicular Environment
WiFi	Wireless-Fidelity

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1

Introduction

Road mobility represents a key component for the economy and welfare of modern society. Only in Europe, the transport sector is estimated to imply expenditures of more than 10% of the Gross Domestic Product (GDP) [1]. Transport services have supported the economy growth in the recent past, and will be crucial to permit a similar trend in the future. Road mobility has a market share of 45% for transportation of goods and of 87% for transport of people [2]. However, the current increase of road traffic is creating problems and challenges that need to be addressed. Accidents, road congestions, and environmental impact are some of these problems. Worldwide, 1.2 million people die in road accidents every year (40.000 Europe), and 50 million are injured. The estimated economic cost of these accidents is between 1% and 2% of the GDP of each country, and amounts to around 518 billion US dollars in total [3]. Moreover, it is currently estimated that daily, 10% of the European road network is affected by traffic congestions [4]. This figure is expected to grow by 50% in 2050 if no action is taken [5]. Traffic congestions cause annual costs between 0.9 and 1.5 % of the EU GDP [6]. Besides this, the increase of road traffic affects energy consumption and provokes non-negligible environmental impact. The energy required by road transport in 2002 represented 26% of the total EU energy consumption, and resulted in 85% of the total CO_2 emissions related to transport. In 2030, these energy demands are expected to increase by 21% [2].

Considering these high societal and economical costs, the need arises to implement new road safety and efficiency measures. In this context, several initiatives were launched in the past years. In 2001, the European Transport Policy established the objective to reduce road fatalities by 50% by the year 2010 [7]. To improve traffic efficiency and reduce environmental impact, road mobility goals were set in the Europe 2020 strategy [8]. Intelligent Transport Systems (ITS) have been identified as powerful means to fulfil these objectives. ITS integrate information and communications technology with transport infrastructure, vehicles and users [9]. Several ITS technologies have been developed and deployed over the past years. These technologies include navigation systems, inductive loops, camera detection systems, in-vehicle sensing technologies, and variable message signs, among others. Despite the benefits brought by these technologies, novel active safety and dynamic traffic management technologies are needed to address the challenges of future road transport.

A major technological breakthrough in road transport and ITS will be cooperative ITS systems. Cooperative ITS systems are expected to improve road traffic safety and efficiency through the dynamic exchange of wireless messages between vehicles (Vehicle-to-Vehicle, V2V), and with infrastructure nodes (Vehicle-to-Infrastructure, V2I). Exchanging information such as vehicles' position and speed will allow detecting potential road hazards and congestions. Disseminating traffic data to interested vehicles will inform them about problematic situations. The objective is to warn drivers with sufficient time to react. Cooperative ITS systems are also expected to offer new means to provide internet services on the move. The expected benefits of cooperative ITS systems motivated the development of dedicated standards in the 5.8-5.9GHz band. The US has led the development of the IEEE 802.11p [10] and WAVE/1609 [11] standards. In Europe, IEEE 802.11p is being adapted by the ETSI Technical Committee on ITS, which is defining the ETSI ITS G5 standard [12]. These standards allow short and medium range communications between vehicles and with Roadside Units (RSUs), and enable the generation of Vehicular Ad-hoc Networks (VANETs). Cooperative ITS systems are not expected to rely on a unique communication technology but can instead exploit the capabilities of heterogeneous communication systems such as cellular networks and broadcasting technologies. Authorities, automotive and telecommunications sectors have internationally recognized the industrial strategic importance of cooperative ITS systems giving rise to initiatives such as COMeSafety [13], the Connected Vehicle Research [14], or the Car-2-Car Communications Consortium (C2C-CC) [15]. Moreover, the role of cooperative systems has been investigated in many ongoing and past international research projects (e.g. [16]-[21]) and piloted in Field Operational Tests (e.g. [22]-[25]).

1.1 Objectives and contributions

Several technical, organizational, economical and legal issues are being studied for the successful deployment of cooperative ITS systems. From a technical perspective, cooperative ITS systems introduce important challenges. These challenges derive from the strict requirements of cooperative ITS applications, as well as from the difficult characteristics of vehicular environments. Cooperative applications can require direct communications, or communications between nodes that are out of range. In the latter case, multi-hop vehicular transmissions relaying the information through intermediate nodes are used. Let us consider a road accident occurring in some point of a road network. One of the vehicles involved in the accident generates a notification message. In order to transfer this message to distant relevant areas, multi-hop vehicular transmissions can be employed. In this context, vehicular routing protocols are needed to route the message to its destination correctly. Over the destination area, the notification has to be reliably and efficiently distributed to interested vehicles. For this purpose, vehicular dissemination protocols are used. The challenges posed by vehicular environments make the design of vehicular routing and dissemination protocols a demanding task. These protocols have to face the high vehicular mobility, the adverse propagation conditions in the 5.9GHz band, and the limited communication resources. In addition, they have to be scalable in the capability to operate in conditions of both high and low vehicular density. In high density scenarios, it is crucial to control the communications overhead to avoid channel congestion. On the other hand, low density situations reduce the presence of relying vehicles and can result in network disconnections. These disconnections may compromise the capability of routing and dissemination protocols to accomplish their objectives.

The objective of this thesis is the design, optimization and evaluation of novel vehicular routing and dissemination protocols that aim at addressing the above mentioned challenges through the use of "multi-hop road connectivity" information. Multi-hop road connectivity is defined as the capability of a road segment to support multi-hop transmissions. The knowledge of road segments exhibiting this capability enables routing and dissemination decisions aimed at ensuring transmission reliability and channel efficiency. The thesis presents a distributed protocol through which vehicles estimate the multi-hop road connectivity in real time. The objective of this mechanism is returning trustful estimates by generating a low amount of communications overhead. Compared to other solutions that try to extrapolate the multi-hop forwarding capability of road segments from vehicular density estimations, the proposed mechanism does not require additional and dedicated messages. On the contrary, it uses standard messages that are necessary for the execution of many cooperative applications. By extending these messages with small-sized information, the proposed mechanism is able to save communications overhead.

Based on these results, the thesis presents a novel vehicular routing protocol exploiting the use of road connectivity estimates. Routing protocols running on a vehicular network have to be capable to dynamically adapt to the network topology changes caused by vehicles' mobility. Moreover, they have to ensure forwarding reliability and channel efficiency in challenging vehicular communication environments. The routing protocol presented in this thesis uses real time road connectivity estimates to adapt its forwarding decisions to the actual connectivity status of the vehicular network. Compared to similar dynamic routing approaches, this adaptive capability is not paid by a significant increase of communications overhead. These approaches always forward messages over road segments with high vehicular density, given that these roads are expected to support reliable multi-hop transmissions. Considering road connectivity estimates allows the presented routing protocol to route messages over multi-hop connected roads independently from the experienced vehicular density. This approach can diminish the probability to transmit messages over the densest roads that are also the most prone to suffer channel congestion. To increase the reliability of message forwarding, a contention-based approach is used by the proposed routing protocol. This contention-based approach is designed to efficiently operate in urban routing scenarios represented as a set of road segments and intersections.

The thesis finally presents a novel hybrid V2X dissemination protocol that also exploits multi-hop road connectivity estimates. This protocol is designed to disseminate messages from a traffic management center (TMC) to vehicles over a relevance area. The TMC could disseminate using individual cellular transmissions, but this might imply traffic and energy issues to network operators. Using only V2V communications might not always ensure adequate service reliability. To overcome these limitations, a framework combining cellular and multi-hop ad-hoc vehicular communications is proposed. The multi-hop connectivity estimated over distinct road segments is collected by the TMC using a cellular uplink channel. At the TMC, this information is processed and fused to achieve a global connectivity context characterization of the VANET. In this way, the TMC learns the sets of road segments where the messages would be reliably disseminated through V2V communications. The TMC uses cellular transmissions to inject messages to specific vehicles in the VANET. In turn, these vehicles start a cooperative V2V dissemination process using multi-hop broadcast transmissions. The TMC uses the acquired context knowledge to implement smart message injection strategies. A limited number of messages are injected to the vehicles that can start a V2V dissemination to reach the highest possible amount of recipient vehicles. In this way, the strategies achieve good delivery performance despite possible VANET disconnections by only requiring a limited number of cellular transmissions. By using lightweight multi-hop road connectivity information, the VANET's connectivity context characterization is obtained using a limited amount of communications overhead.

The presented protocols can be operated in scenarios characterized by a high number of vehicles driving over large areas. Accurate, repeatable and scalable evaluations of such protocols are only viable through simulations. To perform large scale and standard compliant evaluations in a modular way, this thesis has adopted a novel cooperative ITS simulation platform that combines these capabilities in a unique solution. The author of this thesis actively contributed to the design and development of this simulation tool. For this reason, a presentation of the adopted simulation platform is also given in the thesis.

To summarize, the main contributions of this thesis are:

- The definition of a "multi-hop road connectivity" metric to estimate the capability of road segments to support vehicular multi-hop transmissions.
- The design and evaluation of a distributed protocol based on standard V2V transmissions for real time assessments of multi-hop road connectivity.
- The design and evaluation of a novel vehicular routing protocol that exploits real time multi-hop road connectivity estimates to operate dynamic forwarding decisions.
- The implementation of a contention-based forwarding mechanism operating in urban routing scenarios represented as a set of road segments and intersections.
- The definition of a complete framework using heterogeneous communication technologies to obtain a global V2V connectivity context characterization, and exploit this context information for information dissemination.
- The proposal and evaluation of a mechanism with low communications overhead for collecting multi-hop road connectivity information using cellular networks.
- The definition of a processing scheme deriving trustful global VANET's context characterizations using multi-hop road connectivity estimates.
- The design and evaluation of context-driven cellular message injection strategies.
- The design of a multi-hop broadcasting protocol for cooperative V2V message dissemination in urban scenarios.
- The presentation of a novel simulation platform allowing modular, accurate, large scale and standard compliant evaluations of cooperative ITS communication protocols and applications.

1.2 Outline

The rest of this thesis is organized as follows. Chapter 2 presents the development and standardization status of vehicular communications and networks. The requirements of cooperative ITS applications and the challenges of vehicular communications justify the generation of new communication standards and protocols. In this context, the chapter presents the current cooperative ITS standards starting with the adopted communication architectures. In all these architectures, an important role is played by the IEEE 802.11p standard, adapted at European Level by the ETSI ITS G5 specifications. The chapter describes their most relevant characteristics. Chapter 2 also outlines standard GeoNetworking definitions and mechanisms that will enable multi-hop vehicular communications. GeoNetworking standards define the necessary functionalities for the implementation of vehicular GeoRouting and dissemination protocols.

Chapter 3 presents an overview of the most relevant vehicular routing and dissemination protocols presented in the literature. Both routing and dissemination in vehicular environments base their functioning on the concept of GeoNetworking. GeoNetworking, also known as GeoRouting, indicates the capability to forward messages based on the knowledge of nodes' position. This approach provides message forwarding with increased reliability against the negative effects caused by the high mobility of vehicles. Current research trends propose GeoRouting schemes adopting real time traffic information to improve the effectiveness of forwarding decisions. In most of the cases, they use vehicular traffic density estimates to compute reliable end-to-end forwarding paths, but such estimates are obtained at the expense of a high communications overhead. Concerning vehicular dissemination, protocols generally adopt single- and multi-hop broadcast transmissions, and define methods to maintain performance in both low and dense vehicular scenarios. Recent works have started to explore the beneficial effects of using schemes combining V2V communications with other complementary radio technologies.

Chapter 4 presents the simulation platform implemented and used in this thesis. This platform was realized in the framework of an international research project to which the author of this thesis actively contributed. Simulation is an evaluation method capable to tradeoff accuracy, scalability, and repeatability of the experimentations. In addition, it permits to set up different evaluation scenarios in a flexible way. The simulation platform used in this thesis guarantees accurate results by combining realistic vehicular mobility and wireless communication models. Most importantly, it can leverage large scale and standard compliant evaluations of cooperative protocols and applications, which can be implemented over the platform in a very modular way. The description of this simulation platform highlights the key implementation aspects and remarks the novelties compared to similar simulation tools. In this description, particular attention is paid to the adopted wireless models and implementation choices.

Chapter 5 introduces the concept of multi-hop road connectivity. Multi-hop road connectivity represents the capability of a road segment to support multi-hop transmissions. It reflects the presence of relaying vehicles that can forward a message along its length. Vehicular routing and dissemination protocols can use multi-hop road connectivity information to improve their operation and forwarding decisions. The chapter presents and evaluates a distributed mechanism that uses standard V2V transmissions to assess multi-hop road connectivity in real time, and make it available to vehicles in the VANET. Other distributed schemes estimate the connectivity of a road based on the density of vehicles. However, to estimate road density in real time they require additional transmissions that may compromise the channel efficiency. The mechanism proposed in this thesis estimates multi-hop connectivity independently from road density, and hence reduces the communications overhead.

Based on the previous results, Chapter 6 presents and evaluates a novel vehicular GeoRouting protocol able to adapt its routing decisions to the VANET connectivity status. The routing protocol uses multi-hop communications to relay messages from an origin to a destination through a set of road intersections. These intermediate anchor points are dynamically selected based on the estimated multi-hop connectivity of candidate road segments. Other state of the art routing approaches adopt a similar scheme, but select road segments with the highest vehicular density, which are also the most prone to suffering channel congestion. By only considering multi-hop road connectivity irrespectively from the density, the presented protocol reduces the probability to transmit over these roads. To increase the reliability of transmissions, the presented routing protocol adopts a contention-based forwarding approach. This approach is adapted to efficiently operate in routing scenarios consisting of road segments and intersections.

Chapter 7 presents and evaluates a complete framework for dissemination of messages from a TMC to vehicles in a relevance area. This framework concurrently exploits the benefits of multi-hop ad-hoc vehicular communications and wider-range cellular transmissions. The resulting hybrid V2X dissemination is operated in two steps. First, cellular transmissions are used by the TMC to inject a few message copies to specific vehicles. Then, cooperative V2V communications are employed by vehicles to disseminate the injected copies in the VANET. To ensure the delivery of messages to a large number of vehicles, message injections are guided by the knowledge of the VANET's connectivity context. This context characterization is built at the TMC by processing and fusing multi-hop road connectivity estimates collected from the VANET. Based on this context knowledge, the TMC implements smart injection strategies to permit that a few injected messages can result in reliable and effective V2V dissemination. Connectivity context and injection strategies allow achieving good delivery performance against possible VANET disconnections. By distributing and balancing the communications overhead over both the cellular and vehicular ad-hoc networks, the context characterization is obtained with a low communications overhead.

Finally, chapter 8 reports the main conclusions of this thesis, and presents possible future research topics.

2

Vehicular Communications

This chapter presents the development and standardization status of vehicular communications and networks. International efforts have recently defined a set of standard cooperative ITS applications and use cases. The strict requirements of these applications along with the difficulty of vehicular communication conditions pose important technical challenges. Such challenges justified the generation of international standards and architectures for communications in ITS environments. These architectures include radio access technologies, communication and networking protocols and, in general, all the necessary functionalities supporting the execution of cooperative ITS applications.

The rest of the chapter is organized as follows. Section 2.1 outlines a classification of current cooperative ITS applications and use cases. Section 2.2 describes the most significant challenges posed by wireless communications in vehicular environments. The cooperative ITS standards are described in the second part of the chapter. The description starts in Section 2.3 with a summary the adopted communications architectures, followed in Section 2.4 by a detailed presentation of the IEEE 802.11p communication standard that is being adapted at European level by the ETSI ITS G5 specifications. Effective multi-hop communications in vehicular environments will be enabled through the adoption of GeoNetworking communications and protocols. GeoNetworking standards are therefore described in Section 2.5. To conclude this chapter, Section 2.6 describes two important standard facilities offered to cooperative applications: the Cooperative Awareness Service and the Decentralized Environmental Notification Basic Service.

2.1 Vehicular applications and use cases

Cooperative ITS systems can support the practical implementation of a wide range of cooperative ITS applications. Defining and characterizing these applications permits identifying the communication requirements that communication technologies and protocols have to comply with to support them. In this context, the ITS Technical Committee of the European Telecommunications Standards Institute (ETSI TC ITS) has identified a set of reference applications and use cases for the standardization and future deployment of cooperative ITS systems [26]. For the selection of these applications, the actual benefits for the final users as well as the strategic and economical potential for the involved stakeholders have been taken into account. Table 2-1 shows that the selected ETSI ITS applications are classified according to their main objective: active road safety, cooperative traffic efficiency, provision of co-operative local services, and provision of global internet services. For each of the reported applications classes, some possible use cases are indicated. A use case is a practical implementation of a more generic application type. Active road safety applications are classified as either cooperative awareness or road hazard warning applications. Cooperative awareness applications are designed to detect dangerous situations through the continuous exchange of wireless messages between vehicles. For example, the intersection collision warning use case can warn drivers about an imminent collision at an intersection detected by the V2V exchange of broadcast messages. Road hazard warning applications are in charge of the instantaneous environmental notification of dangerous events upon their occurrence on the road network. In this case, a representative example is the notification of a stationary vehicle on the road. In this case, a stationary vehicle can alert other vehicles of its presence using V2V communications. Traffic efficiency applications are designed to improve traffic conditions and management. For example, they will inform drivers about the need to adjust their driving speed (speed management), or modify their current routes (cooperative navigation applications). In this context, a typical example of speed management use case is the notification of contextual or regulatory speed limit messages periodically broadcasted by a RSU to passing-by vehicles. A representative use case of cooperative navigation applications is the provision of traffic information and recommended itinerary. In this use case, a RSU can inform approaching vehicles about abnormal situations like traffic congestions in specific areas of the road network. Cooperative local and global internet services provide information to vehicles, such as infotainment, comfort, and vehicle or service life cycle management. Cooperative local services should be provided directly to vehicles from the ITS network infrastructure. On the other hand, global internet services are supplied by external providers.

Applications Class	**Applications**	**Use cases**
Active road safety	Driving assistance - Cooperative awareness	Emergency vehicle warning
		Slow vehicle indication
		Intersection collision warning
		Motorcycle approaching indication
	Driving assistance - Road Hazard Warning	Emergency electronic brake lights
		Wrong way driving warning
		Stationary vehicle - accident
		Stationary vehicle - vehicle problem
		Traffic condition warning
		Signal violation warning
		Roadwork warning
		Collision risk warning
		…
Cooperative traffic efficiency	Speed management	Regulatory / contextual speed limits notification
		Traffic light optimal speed advisory
	Cooperative navigation	Traffic information and recommended itinerary
		Enhanced route guidance and navigation
		Limited access warning and detour notification
		In-vehicle signage
Cooperative local services	Location based services	Point of Interest notification
		Automatic access control and parking management
		ITS local electronic commerce
		Media downloading
Global internet services	Communities services	Insurance and financial services
		Fleet management
		Loading zone management
	ITS station life cycle management	Vehicle software / data provisioning and update
		Vehicle and RSU data calibration

Table 2-1. Basic set of ETSI cooperative ITS applications [26].

Each of the identified applications and use cases has distinct requirements in terms of communication settings and performance requirements [26]. For example, vehicles should be able to broadcast messages at a minimum frequency; receive information with a maximum latency; ensure a given radio coverage, etc. ETSI definitions report fixed reference values for the communication requirements of each specific use case, with those of active road safety applications being generally stricter than those of traffic efficiency applications. For example, an intersection warning application requires broadcasting messages at a minimum frequency of 10Hz, and receiving messages with a maximum latency of 100ms. On the other hand, a traffic information application can initially tolerate latencies of 500ms and work with a broadcasting frequency of 1Hz. These differences are due to the need to increase the robustness and reliability of active safety applications.

Moreover, for a correct execution, applications have to respect other operational requirements. These requirements include the availability of digital road maps, the capability to obtain accurate vehicle positioning information, and the availability of authentication and security mechanisms to protect against malicious attacks. From a communication point of view, broadcasting, multicasting, and ad-hoc networking capabilities are key operational requirements for the execution of cooperative applications [26]. The communication capabilities of cooperative ITS applications can be further extended using multi-hop communications to address recipient nodes or target areas that cannot be directly reached through single-hop transmissions. For example, traffic information concerning local traffic congestion could be notified to distant vehicles using multi-hop transmissions.

2.2 Vehicular communication challenges

The design and development of cooperative ITS systems is strongly influenced by the encountered wireless communication challenges in vehicular environments. Identifying technical countermeasures to solve these challenges is a key issue for a successful deployment of cooperative ITS systems. In the following, some of the common challenges related to vehicular communications are discussed:

- *Possible lack of management infrastructure.* Cooperative ITS applications can be supported by traditional infrastructure-based communication systems like cellular networks. In these traditional communication systems, the available bandwidth is administrated by centralized entities. These entities also manage transport and addressing of information among communicating nodes. However, certain cooperative applications require vehicles to be able to rapidly exchange information over VANETs. In some cases, VANETs can leverage the presence of RSUs.

Although forming part of the communication infrastructure, RSUs do not implement management functions. As a result, in VANETs, vehicles have to implement distributed management techniques to dynamically and efficiently administrate the channel access and the use of radio resources. Moreover, for communications over long distances, vehicles have to adopt distributed multi-hop communication protocols.

- *Vehicular mobility.* Vehicular communications and networking are significantly challenged by the high mobility of nodes. Under high speeds, radio link propagation conditions rapidly change. Specific countermeasures are then necessary to adapt to such changes and ensure the reliability of vehicular communications. Moreover, the high speed of vehicles requires a rapid execution of information exchange, as this may be critical to support cooperative ITS applications. The mobility of vehicles also results in frequent changes VANETs' topology. These topology changes make multi-hop communications and networking difficult. In this context, novel routing schemes are needed in vehicular environments.
- *Radio propagation conditions.* Vehicular communication environments are characterized by rapid variations of the radio channel and link conditions. Vehicular communications are further impaired by the low vehicular antenna heights and the use of high frequencies (5.9GHz). These features increase the radio signal attenuation, especially in the presence of obstacles like buildings, trees or other vehicles, which are typical in vehicular environments.
- *Scalability.* Vehicular communications are required to maintain their effectiveness in sparse as well as in highly dense vehicular networks. In this context, the scalability of vehicular networks has been shown to be a significant technical challenge. Low vehicular densities are characterised by a scarce presence of forwarding nodes that complicate multi-hop transmissions to distant destinations. In this scenario, store-carry and forward schemes could permit multi-hop communications to keep their operation at the cost of increasing the end-to-end latency. The most relevant challenge encountered under high vehicular densities is the prevention of congestion in the radio channel. This is particularly important considering that a number of coexisting cooperative applications are expected to operate in the same vehicular communication channels.
- *Security and privacy.* Vehicular applications will involve the exchange of information between vehicles and infrastructure nodes. This information needs to be protected against external malicious attacks. Moreover, the privacy of the actors involved in this information exchange has to be guaranteed.

2.3 Vehicular communication standards

Various standardization bodies are actively contributing towards the development of vehicular communications. The Technical Committee 204, Working Group 16 of the International Organization for Standardization (ISO TC204 WG16) has developed a family of international standards for the ITS domain, based on the so-called CALM (Communications Access for Land Mobiles) architecture [27]. The CALM family of standards specifies a communications architecture, network protocols and communication interfaces for wired and wireless transmissions in vehicular environments. In particular, it defines the possibility to simultaneously provide cooperative services over various heterogeneous and complementary radio access technologies such as cellular 3G/4G, satellite, infra-red, 5GHz micro-wave, 5.9GHz IEEE 802.11p/ETSI ITS G5, 60GHz millimetre-wave, and so on. CALM standards cover all the layers of the ISO/OSI architecture, and define various types of communication scenarios (e.g. direct and multi-hop, V2V, V2I, Internet access) and transmission modes (e.g. unicast, multicast, broadcast and geocast). A key contribution of CALM is the approach to abstract cooperative applications from the underlying radio access technologies and transport/networking schemes. In this context, CALM foresees heterogeneous handover or Media Independent Handover (MIH) methods for seamless application provision between the various access technologies supporting cooperative ITS services.

At European level, the implementation of cooperative ITS systems is being fostered by the ETSI TC ITS. This technical committee is developing similar standard specifications to those proposed by ISO CALM under the framework of the ITS architecture for Intelligent Transport Systems Communications (ITSC) [28]. The ITSC architecture defines four main communication sub-systems for the execution of cooperative ITS applications. A Personal ITS sub-system is a handheld communication device (e.g. a smartphone). A Central ITS sub-system is a Traffic Management Center (TMC) responsible for the centralized control of road traffic. In order to disseminate road traffic information to vehicles or collect floating car data, a Central ITS sub-system can be connected to a Roadside ITS sub-system (i.e. an IEEE 802.11p/ETSI ITS G5-based RSU) or other communication infrastructure nodes (e.g. 3G/4G cellular, WiMAX or DVB base stations). Finally, a Vehicle ITS sub-system is a connected vehicle capable to communicate with other vehicles and infrastructure nodes to execute cooperative ITS applications.

The ITSC communication sub-systems implement the architecture illustrated in Figure 2-1. Cooperative ITS applications can be supported by various radio access technologies. As previously mentioned, the ETSI ITS G5 standard [12] adapts at European level the specifications of the IEEE 802.11p communication standard [10], specifically developed to enable reliable communications between vehicles and with RSUs. Although 802.11p/ITS G5 is expected to be the dominant communication technology for cooperative ITS communications and applications, other technologies can be used. As a result, the Access Technologies layer includes a variety of communication technologies enabling short-range, broadcast and cellular-type communications. The Transport & Network layer includes two different protocol stacks. The GeoNetworking or Car-to-Car (C2C) Stack implements specific addressing schemes, GeoRouting and transport protocols based on ITS G5 ad-hoc capabilities. The IP Stack supports pre-existing TCP/UDP transport and IP networking protocols. IP protocols in both versions 4 and 6 are considered, with IPv6 adaptations enabling a better management of addressing in vehicular environments. The Facilities layer includes a set of common functionalities and data structures to support cooperative ITS applications and communications. They can be classified into Application Support, Information Support and Communication Support facilities. An important facility is the Local Dynamic Map (LDM), which stores and manages dynamic information characterizing the local neighborhood of vehicles and RSUs. This information can be collected through exchanged cooperative messages or on-board sensors. The information stored in the LDM can then be used by the cooperative ITS applications that exploit the underlying functionalities of the facilities to provide road safety, traffic management and infotainment services. The vertical Management layer is responsible for monitoring and management functionalities over ITS stations. For example, it coordinates the cross-layer exchange of information, and determines the optimal mapping of cooperative ITS applications onto the available set of radio access technologies, transport and network protocols. Finally, the Security layer provides the necessary security and protection mechanisms for the complete communication stack in order to resist to external attacks, guarantee the user's privacy, and ensure a trustworthy exchange of information.

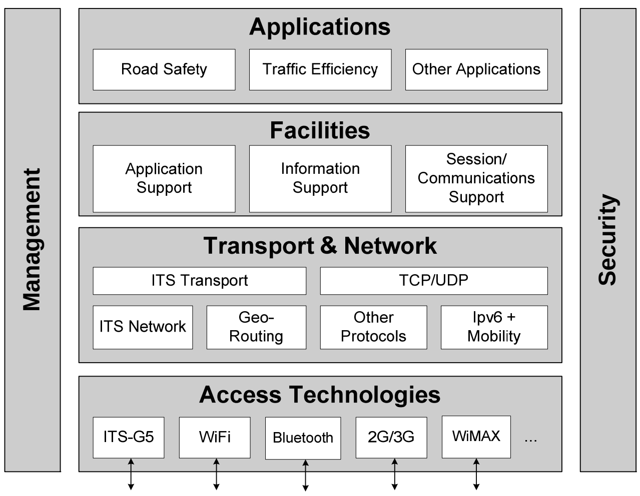


Figure 2-1. ETSI ITS Architecture for Intelligent Transport Systems Communications [28].

Important activities for the standardization of cooperative ITS systems have been also performed within the IEEE that defined the specifications for the Wireless Access in Vehicular Environment (WAVE) protocol stack [11] (Figure 2-2). The IEEE WAVE protocol stack only considers the IEEE 802.11p communication standard as radio access technology for the provision of cooperative ITS applications. The upper layers of the communication stack are implemented according to the specifications of the IEEE 1609 standards. The protocols belonging to the IEEE 1609 standards family concern the management of resources, networking and security services, as well as multi-channel operations.

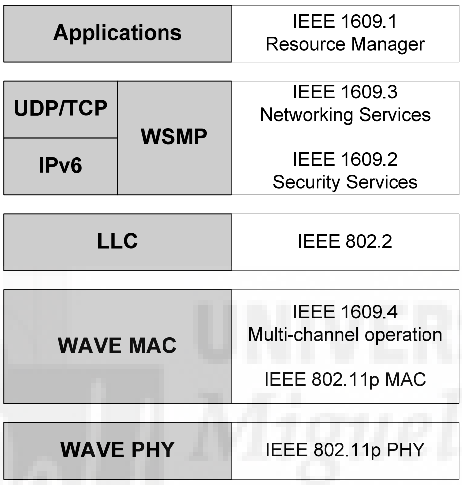


Figure 2-2. IEEE WAVE protocol stack.

2.4 IEEE 802.11p/ETSI ITS G5

The IEEE 802.11p communication standard, adapted at European level by the ETSI ITS G5 definitions, is expected to be the dominant radio technology for the provision of cooperative ITS services and applications. IEEE 802.11p amends the IEEE 802.11 standard [29] to allow fast and reliable V2V and V2I single- and multi-hop communications in challenging vehicular environments.

2.4.1 Radio channel allocation

Various 10MHz-channels have been reserved for vehicular communications in the 5.9GHz band in various parts of the world, including Europe and the US (Figure 2-3). In the US, a 75MHz bandwidth was allocated on the Dedicated Short Range Communications (DSRC) spectrum band. A similar allocation was performed in Europe. In this case, the 30Mhz band from 5.875 to 5.905GHz was allocated in three channels and referred to as ITS G5A band. The two channels in the band from 5.855 to 5.875GHz are referred to ITS G5B. The two channels from 5.905 to 5.925GHz have been dedicated future extensions. Moreover, the band between 5.470 and 5.725GHz (not shown in the figure) has also been dedicated for future vehicular applications' use and is referred to as ITS G5C. IEEE and ETSI standards define the limits in terms of transmission power (in dBm EIRP) and transmission power density (in dBm/MHz) to be applied to each of these channels [12][29].

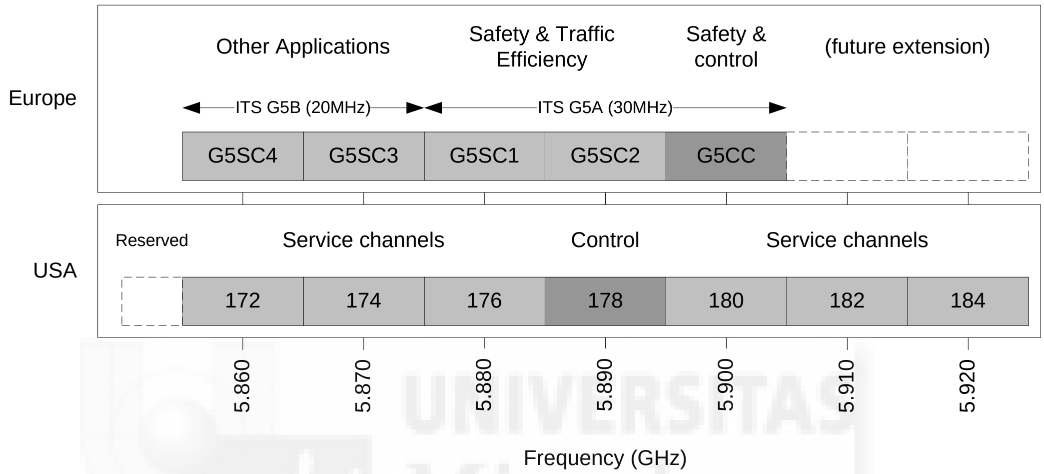


Figure 2-3. Frequency allocation for vehicular communication systems in Europe and the US.

As depicted in Figure 2-3, one of the channels is referred to as control channel, while the others are service channels. The control channel (G5CC in the European standard) is the reference channel where every vehicle periodically broadcasts control information to inform other vehicles about its presence and status. It is also expected to support most of the wireless transmissions needed for road safety vehicular applications. In addition, the control channel will be used to announce transmissions for applications taking place on the service channels. In this context, this channel acts as reference channel and all vehicles need to constantly check for possible messages on it. The service channels are used for safety and non-safety communications. In Europe, G5SC1 is the main service channel for safety and traffic efficiency messages. The use of G5SC1 is foreseen for high throughput safety messages with medium priority. On the other hand, G5SC2 will be used for low power transmissions and short-range communications. This is to reduce the co-channel interference that G5SC2 transmissions could create on the adjacent G5CC and G5SC1.

2.4.2 Physical layer

The PHY layer of IEEE 802.11p is an evolution of the IEEE 802.11a standard operating at the 5GHz frequency band. Compared to 802.11a, it is designed to operate on 10Mhz channels. Differently from the 802.11a's 20MHz channels, 10MHz channels are adopted in vehicular environments to better handle the effects of multipath delay spread, especially under high vehicular speeds. The use of 10MHz channels permits the adoption of guard intervals long enough to prevent worst-case inter-symbol interferences. IEEE 802.11 already defines using 10MHz wide channels, hence the implementation of 802.11p only requires doubling all the timing parameters adopted by the IEEE 802.11a standard for its OFDM (Orthogonal Frequency Division Multiplexing) modulation and coding schemes. Like 802.11a, 802.11p considers 52 subcarriers that are modulated using BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying), 16-QAM (16-Quadrature Amplitude Modulation) or 64-QAM. Moreover, Forward Error Correction (FEC) convolutional coding is used with a coding rate of 1/2, 2/3, or 3/4. The resulting data rates associated to these modulation and coding schemes for 10MHz and 20MHz channels are reported in Table 2-2. To mitigate potential co-channel interferences, IEEE 802.11p introduces improved receiver performance requirements in terms of adjacent channel rejections. In particular, four improved transmission spectrum masks are defined to be more stringent than those demanded to current 802.11 radios.

Data rate for 10MHz [Mbps] IEEE 802.11p	**Data rate for 20MHz [Mbps] IEEE 802.11a**	**Modulation**	**Coding rate**
3	6	BPSK	1/2
4.5	9	BPSK	3/4
6	12	QPSK	1/2
9	18	QPSK	3/4
12	24	16-QAM	1/2
18	36	16-QAM	3/4
24	48	64-QAM	2/3
27	54	64-QAM	3/4

Table 2-2. IEEE 802.11p and IEEE 802.11a data rates.

2.4.3 Medium access control

To manage the distributed access to the shared wireless medium, IEEE 802.11p adopts a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol following the specifications of IEEE 802.11's Distributed Coordination Function (DCF). Before transmitting a packet, a node listens to the radio channel to verify whether any other transmission is ongoing. If the channel is detected as free for at least DIFS (Distributed Inter Frame Space) microseconds, the node transmits. Otherwise, the node has to wait until the end of the ongoing transmission. At the end of the ongoing transmission, the node activates a backoff timer whose expiration triggers the packet transmission. The duration of this backoff timer is random in order to avoid that two or more nodes waiting to access the wireless medium activate their transmissions at the same time and produce packet collisions. The duration of the backoff timer is uniformly distributed over a contention window (CW) composed by a given number of time slots (13µs long for 10MHz channel bandwidth). The length of the CW varies according to the outcome of packet transmissions. Initially, the CW length is set to a minimum value. For each transmission failure, the CW is doubled until reaching its possible maximum value. When successful transmissions take place, the CW is reset to the minimum value. This process allows adapting the backoff timer to the current channel load status. Packet failures can be detected for unicast transmissions thanks to an acknowledgement mechanism. A packet retransmission is scheduled every time an acknowledgment (ACK) is not received from the destination node. However, this acknowledgement mechanism cannot be applied to broadcast transmissions. For broadcast transmissions, the CW length is always set to the minimum value.

Despite the adopted backoff scheme, packet collisions can still occur in IEEE 802.11p due to the well-known hidden node problem. The hidden node problem causes packet collisions at receiving nodes placed between transmitters that cannot detect each other's transmissions. This problem is particularly relevant in vehicular environments since transmitters can be mutually hidden by medium- and large-sized obstacles blocking the radio signals. The hidden node problem can be addressed for unicast transmissions with a virtual carrier sensing mechanism. In this case, every transmission is previously announced by a small Request To Send (RTS), and then allowed by the receiver through a Clear To Send (CTS) packet. However, this can lower the overall throughput as a result of increased transmission delays. Most importantly, it cannot be applied to broadcast transmissions, and hence it is useless for a number of vehicular applications that rely on broadcast communications.

The IEEE 802.11p MAC layer can also differentiate data traffic based on its quality of service (QoS) requirements. This is accomplished by adopting the Enhanced Distributed

Channel Access (EDCA) mechanism defined by the IEEE 802.11e standard. This standard defines four different access categories (AC) for different types of data traffic (e.g. safety or non-safety traffic). Data belonging to different access categories are scheduled in distinct queues. Each queue accesses the channel using its own channel sensing and backoff timer procedures. Distinct queues present different CW minimum and maximum lengths, as well as different DIFS durations (DIFS is known as AIFS in IEEE 802.11e). In this way, packets belonging to applications with distinct QoS requirements are assigned a different priority for the access to the wireless medium.

The requirements of vehicular applications and the challenges encountered in vehicular environments require minimizing the time and overhead needed to execute communications. For this purpose, IEEE 802.11p has introduced various amendments to the original 802.11 standard at MAC level. In particular, using IEEE 802.11p vehicles do not have to perform association and authentication mechanisms to join a BSS (Basic Service Set) or an IBSS (Independent BSS). A BSS is a set of IEEE 802.11 nodes being able to communicate on the same channel through the same access point. An IBSS is a set of nodes connected through an ad-hoc network. 802.11p nodes do not have to perform frequency scanning procedures to discover existing BSSs or IBSSs. Instead, vehicular standards define specific functionalities to operate on the identified vehicular frequency channels, as described in the next section.

2.4.4 Multi-channel operation

IEEE 802.11p and ETSI ITS G5 require that vehicles communicate over the control and service channels. How such multi-channel communications are managed depends on the specific standard. The IEEE 802.11p standard operating over the WAVE communication stack follows the specifications of the IEEE 1609.4 standard [11]. This standard defines the use of a single transceiver. A 802.11p transceiver must then switch between the control channel and one of the service channels at regular time slots. The control channel is used to transmit safety related messages, and to advertise messages that will be transmitted on a specific service channel during the next time slot. By overhearing an advertisement, receiving nodes tune the transceiver on the specified service channel at the beginning of the next slot.

The European ETSI ITS G5 adaptation specifies that every ITS G5 station must be able to simultaneously receive on the G5CC and one of the G5SCs, except when transmitting in any of these channels [12]. This implies that vehicles and RSUs can be equipped with two radio transceivers with one of them always operating on the control channel. The other transceiver should be able to switch between the service channels.

Messages transmitted on the service channels are also previously announced on the control channel by means of Service Announcement Messages [30].

2.5 GeoNetworking

One distinguishing feature of the European ETSI ITSC architecture (Figure 2-1) is the specification of standard functionalities enabling GeoNetworking transmissions in vehicular environments. GeoNetworking or GeoRouting transmissions provide ad-hoc and multi-hop communications over short-range wireless technologies (such as ETSI ITS G5). In such communications, nodes are addressed using not only their network addresses but also their geographical positions. GeoNetworking transmissions enable vehicular point-to-point as well as point-to-multipoint communications. In case of point-to-point communications, GeoNetworking transmissions overcome the inefficiencies resulting from classical MANET schemes that transmit packets over end-to-end routes reactively computed or proactively maintained. The high mobility of vehicles would cause frequent topology changes that compromise the time validity of established end-to-end routes. To address this problem, GeoNetworking schemes dynamically select the forwarding nodes at each hop based on their geographical position with respect to the position of the destination. Vehicles obtain the knowledge of their own positions from on-board GPS devices. Moreover, every node informs its neighbors about its position by continuously broadcasting beacon messages. For point-to-multipoint communications, the use of geographical positions allows restricting radio transmissions' addressing only to the vehicles belonging to circumscribed areas (geocasting). In this way, it is possible to enable a number of cooperative ITS applications using messages that have relevance only in specific zones of the road network.

As depicted in Figure 2-1, GeoRouting mechanisms are specified in the GeoNetworking stack of the ETSI ITSC Transport & Network layer [31]. GeoRouting mechanisms are associated to a specific ITS transport protocol called Basic Transport Protocol (BTP) [32]. The main purpose of the BTP is multiplexing/demultiplexing messages from/to the upper layers based on a 16 bit address. This address represents a communication end-point responsible for handling the message at both source and destination nodes. In order to support fast execution of vehicular applications, BTP is a very lightweight protocol requiring minimal processing. However, it cannot ensure a reliable end-to-end packet transport, i.e. packet can arrive out of order, duplicated or can be lost. The Transport & Network layer of the ITSC architecture also defines the IP stack. This communication stack includes the IP protocol (IPv4 and IPv6) along with pre-existing transport protocols such as UDP and TCP, and is necessary to implement cooperative ITS services that require connection to core networks. The above mentioned

GeoNetworking and IP stacks can be also combined in such a way to run the IP protocol on the top of the GeoNetworking protocol (IP over GeoNetworking stack). In this case, IPv6 packets are encapsulated into GeoNetworking packets using a header tunnelling method, and forwarded with a specific GeoRouting protocol to the destination.

2.5.1 GeoNetworking transmission modes

GeoNetworking transmissions can be classified according to the type of destination used to address messages. For example, the destination can be a single node whose geographical location is known, or a set of nodes placed within a geo-referenced area. For this classification, the ETSI standard [33] reuses the definitions of the GeoNet research project [34]. Four basic GeoNetworking transmission modes are identified, namely GeoUnicast, GeoAnycast, GeoBroadcast, and TopoBroadcast.

GeoUnicast refers to a point-to-point communication scenario in which a message transmitted by a source node has to reach a single destination node whose geographical location is known (Figure 2-4). Relaying nodes take forwarding decisions using the information about the location of the destination node.

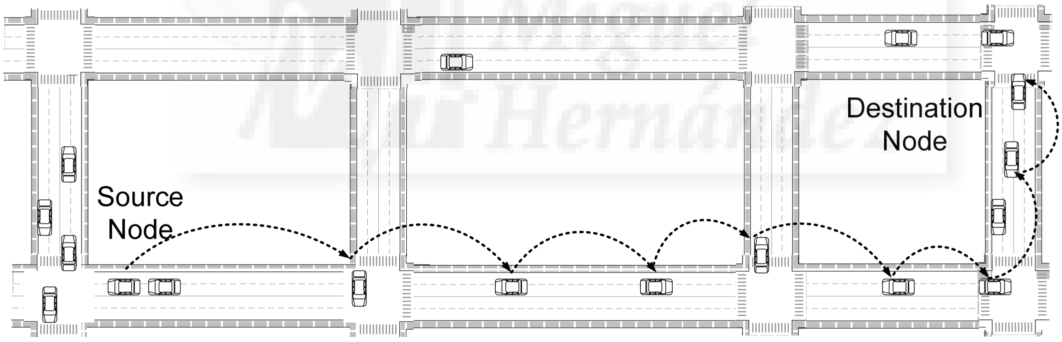


Figure 2-4. GeoUnicast communications.

GeoAnycast refers to a transmission mode in which a message transmitted by a given source has to reach any node placed within a specific geo-referenced area (Figure 2-5). As for the GeoUnicast scenario, intermediate nodes take their forwarding decisions based on the geographical position of the destination. In the case of GeoAnycast communications, the destination is not identified by the location of a node, but by an area specified in terms of center and sprawl (e.g. if the destination area is a circle, it can be represented by center and radius). The first node that receives the message in the destination area is the destination of the message.

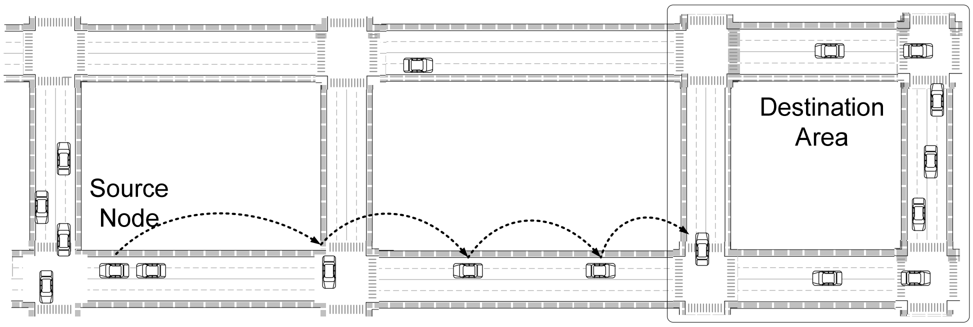


Figure 2-5. GeoAnycast communications.

GeoBroadcast refers to a point-to-multipoint communication scenario in which a message transmitted by a source node has to be delivered to all the nodes placed over a given geo-referenced destination area (Figure 2-6). In GeoBroadcast, the source node may be located inside or outside the targeted area. If the source node is already in the targeted area, it broadcasts the message. Otherwise, it starts a GeoAnycast transmission towards the destination area. To ensure that every node in the destination area receives the message, various methods can be used. The method specified by GeoNet indicates that every node receiving the message in the destination area has to rebroadcast it once (simple flooding).

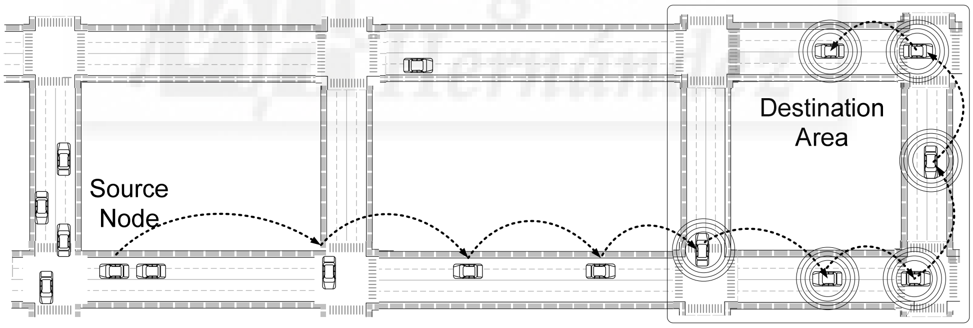


Figure 2-6. GeoBroadcast communications.

TopoBroadcast, or Topologically-scoped Broadcast (TSB), is another point-to-multipoint communication scenario. In this scenario, a message transmitted by a source node has to be broadcasted for a given number of hops specified by a hop limit (HL) value. Figure 2-7 represents a TopoBroadcast communication scenario in which the HL is set to three hops.

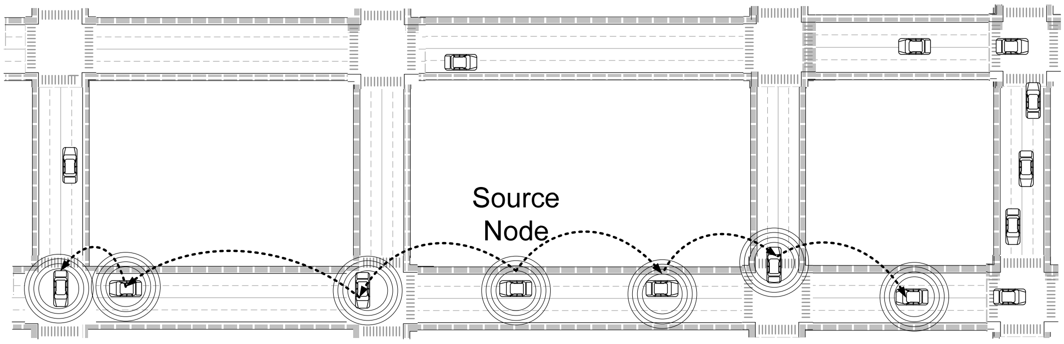


Figure 2-7. TopoBroadcast communications.

2.5.2 Standard GeoNetworking functionalities

The GeoNetworking communication stack of the ETSI ITSC architecture includes all the functionalities necessary to implement GeoNetworking transmissions [33]. These functionalities are common for any ad-hoc short-range wireless access technology, hence they are not initially limited to ETSI ITS G5. According to [33], every node (ITS station) involved in any of the above-mentioned GeoNetworking transmission modes is identified by a GeoNetworking Address. The GeoNetworking address is coded with 8 bytes and is composed by various fields such as the MAC layer address of the wireless interface, the ITS station type (e.g. vehicle or RSU), the ITS station subtype (e.g. public transport or private vehicle), and a code specifying the country to which the ITS station belongs. In case of transmissions requiring IP addressing over the GeoNetworking stack, nodes are identified with both a GeoNetworking and an IP address. In these cases, specific methods are used to identify a GeoNetworking address starting from an IPv6 address.

A node locally maintains a data structure called Local Position Vector (LPV) containing personal geographical information obtained through on-board GPS systems. In particular, the LPV contains the ITS station's geographical coordinates, its speed, heading direction, the accuracy of all this information as well as the timestamp of when it was last generated. Besides updating personal geographical information, an ITS station has also to be informed about location and movement of other nodes. This knowledge is necessary for GeoNetworking transmissions. For this purpose, every ITS station locally maintains another data structure called Location Table that stores specific entries for all the known nodes. The Location Table entry referring to a given node contains its GeoNetworking address, its Position Vector (i.e. geographical coordinates, speed, heading direction, timestamp, accuracy), an indicator of whether this node is currently a neighbour (i.e. whether it is in direct communications range), and a sequence number (SN) of the last GeoNetworking packet received from this node. Location Table entries are updated upon reception of GeoNetworking packets from neighbour nodes. If an entry is not updated by an expiration deadline (20s according to [33]), it is removed from the Location Table.

A GeoNetworking Packet is a packet adopted to implement GeoNetworking transmissions. The structure of a GeoNetworking packet is depicted in Figure 2-8. The figure also represents the MAC header of the adopted radio access technology. The MAC header contains the MAC address of the GeoNetworking packet's next hop. The GeoNetworking Security Header is an optional field that can be used to protect GeoNetworking transmissions against external attacks and ensure the privacy of the involved communicating nodes. The Payload represents the user data generated by upper protocol entities, and passed to the GeoNetworking layer for transmission (it is optional). The GeoNetworking Header is the header introduced to the packet by the GeoNetworking layer. It consists of a Common Header that is common for every type of GeoNetworking transmissions, and an optional Extended Header that is differently specified for distinct GeoNetworking transmission modes (Section 2.5.1). The Common Header is the most important part of every GeoNetworking packet as it carries the geographical information of the node that is transmitting the packet. By analyzing this header, receiving nodes can update their Location Table and reuse this information for GeoNetworking purposes. Moreover, the Common Header contains useful information to instruct receiving nodes about how to handle the received packet, i.e. according to what GeoNetworking transmission mode the packet has to be forwarded, or eventually delivered to the upper layers of the communication stack. The various fields of the Common Header are described in Table 2-4.

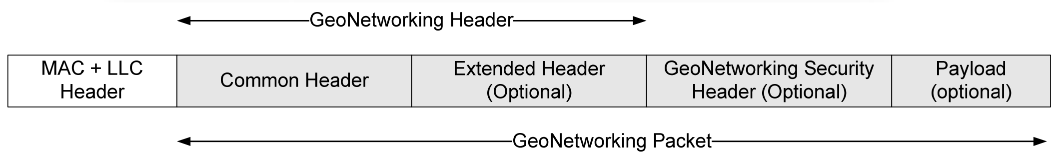


Figure 2-8. GeoNetworking packet structure.

The Header Type field of the Common Header indicates the GeoNetworking transmission mode adopted for the transmission of the packet. Besides the transmission modes listed in Section 2.5.1, the ETSI standard [33] defines the Beaconing Protocol that is used by every ITS station to advertise its location and movement to neighbouring nodes. This is accomplished by broadcasting Beacon messages only containing the Common Header (and hence the Position Vector of the node) at regular time intervals, unless other GeoNetworking packets are broadcasted. For this purpose, a timer whose expiration triggers the transmission of a Beacon message is defined. The timer is reset every time a new GeoNetworking packet is broadcasted. When receiving a

GeoNetworking packet, a node processes the Common Header first. It extracts the Sender Position Vector field of the Common Header and updates the Location Table's entry of the packet's sender with new location information. Then, it checks the Header Type field to realize if an Extended Header is attached to the Common Header. If yes, the packet has to be handled by a protocol specifying the rules to implement one of the transmission modes specified in Section 2.5.1. The Header Type field specifies which protocol has to be used (e.g. GeoUnicast, GeoBroadcast, etc.). For every transmission mode, the standard [33] defines the Extended Header formats to be used. For GeoUnicast transmissions, the format described in Table 2-4 is adopted.

Field Name	**Length [Bytes]**	**Description**
Version	0.5	Indicates the version of the GeoNetworking Protocol
Next Header	0.5	Identifies the type of packet's header immediately following the GeoNetworking header (e.g. BTP or IPv6)
Header Type	0.5	Identifies the GeoNetworking Extended Header type following the Common Header. Distinct Extended Header types are used for different GeoNetworking transmission modes (e.g. GeoUnicast, GeoBroadcast, Beacon transmissions, etc.)
Header Sub-Type	0.5	Identifies the sub-type of a specific GeoNetworking transmission mode (e.g. GeoBroadcast with circular or GeoBroadcast with rectangular destination area)
Reserved	1	Reserved for specific functionalities of the adopted wireless access technology
Flags	1	Flags reserved for future uses.
Payload	2	Indicates the length of the payload following the GeoNetworking header, if any
Traffic Class	1	Represents requirements imposed by the higher layers on packet transport
Hop Length	1	Is set to a given value by the packet source and decremented by 1 by each forwarding node. The packet must not be forwarded when this value reaches zero
Sender Position Vector	28	Contains the Position Vector of the node that is sending the packet

Table 2-3. GeoNetworking Common Header's fields.

The source of a GeoUnicast packet sets all the fields indicated in Table 2-4 before transmitting the packet. At intermediate forwarding nodes, the Source Position Vector and Destination Position Vector fields are used to update the Location Table's entries of the packet's sender and destination nodes. More importantly, the Destination Position Vector is analyzed for the selection of the next hop. For example, a forwarder may search in its Location Table the closest neighbouring node to the targeted destination and transmit the packet to this node. At every hop, a receiving node analyzes the GeoNetworking address contained in the Destination Position Vector to check whether it is the destination of the packet. If this is the case, the payload contained in the packet is forwarded to the upper layers of the communication stack.

Field Name	**Length [Bytes]**	**Description**
Sequence Number	2	Indicates the index of the GeoUnicast packet. It is used to detect duplicate GeoUnicast packets
Life Time	1	Indicates the maximum tolerable time a packet can be buffered until it reaches its destination
Reserved	1	Reserved for specific functionalities of the adopted wireless access technology
Source Position Vector	28	Contains the Position Vector of the node that originated the packet
Destination Position Vector	20	Contains the Position Vector of the node that is targeted by the packet

Table 2-4. GeoUnicast Extended Header's fields.

For both GeoAnycast and GeoBroadcast transmissions, the Extended Header format described in Table 2-5 is used. Most of the fields are equal to those used for the GeoUnicast Extended Header, and processed in the same way at forwarding nodes. The destination area is represented by the geographical position of its center (GeoArea Position field). Various other fields specify the sprawl of the area. For GeoAnycast transmissions, a receiving node checks the GeoArea Position and Sprawl fields to understand whether it is the first node receiving the packet in the destination area. If it is the case, the message contained in the packet is forwarded to the upper layers. In the case of GeoBroadcast transmissions, every node receiving the packet in the destination area broadcasts the packet once, and forwards payload to the upper layers of the communication stack.

Field Name	Length [Bytes]	Description
Sequence Number	2	Indicates the index of the packet. It is used to detect duplicate packets
Life Time	1	Indicates the maximum tolerable time a packet can be buffered until it reaches its destination
Reserved	1	Reserved for specific functionalities of the adopted wireless access technology
Source Position Vector	28	Contains the Position Vector of the node that originated the packet
GeoArea Position	8	Specifies longitude and latitude of the center of the destination area
GeoArea Sprawl	8	Specifies the sprawl of the destination area. It is composed by different fields that are coded in distinct ways according to the shape of the destination area

Table 2-5. GeoAnycast/GeoBroadcast Extended Header's fields.

For TopoBroadcast transmissions, the Extended Header format is described in Table 2-6. Since the packet has to be broadcasted for a given number of hops, no fields specifying a destination are included. The number of hops is specified in the Hop Limit field of the Common Header (Table 2-3). Every node receiving a TopoBroadcast packet forwards the payload to the upper layers. Moreover, it decrements by one the value contained in the Common Header's Hop Limit field, and rebroadcasts the packet once. The packet is not further broadcasted when the Hop Limit is equal to zero.

Field Name	Length [Bytes]	Description
Sequence Number	2	Indicates the index of the sent GeoUnicast packet. It is used to detect duplicate GeoNetworking packets
Life Time	1	Indicates the maximum tolerable time a packet can be buffered until it reaches its destination
Reserved	1	Reserved for specific functionalities of the adopted wireless access technology
Source Position Vector	28	Contains the position vector of the node that originated the packet.

Table 2-6. TopoBroadcast Extended Header's fields.

2.6 Cooperative Awareness and Decentralized Environmental Notification services

Two of the most important functionalities offered to cooperative ITS applications by the Facilities layer of the ETSI ITSC architecture are the Cooperative Awareness and the Decentralized Environmental Notification Basic Services. Both services belong to the Application Support Facilities of the ETSI ITSC architecture (Figure 2-1). The Cooperative Awareness Basic Service [35] periodically generates Cooperative Awareness Messages (CAMs) broadcasted by vehicles and RSUs using single-hop GeoNetworking packets (i.e. packets only carrying the GeoNetworking Common Header specified in Section 2.5.2). CAMs are broadcasted by ETSI ITS G5 radio interfaces over the ITS G5 control channel (ITS G5CC). Through CAM messages, every vehicle or RSU provides to its neighbouring nodes with information about its presence, position, movement, basic attributes (e.g. vehicle's type, dimensions, etc.) and sensor information (e.g. vehicle's door open, vehicle's lights in use, etc.). At receiving nodes, the information contained in CAM messages is extracted and stored in other Facilities (e.g. the LDM), where it is made available to cooperative applications. These applications can check the relevance of the received information based on the current context, and act accordingly. As an example, a collision warning application running on two vehicles approaching the same intersection can analyze the information extracted by exchanged CAMs to check whether the vehicles are prone to collide. If this is the case, the application reacts by warning the drivers about the imminent risk. Due the critical nature of many vehicular applications, CAM messages have to be broadcasted frequently. In particular, the ETSI standard [35] specifies a CAM transmission frequency in the range [1-10Hz]. This frequency range is higher than that adopted at the GeoNetworking layer for the transmission of Beacon messages. As defined in Section 2.5.2, a node does not transmit a Beacon message if it broadcasted another GeoNetworking packet (in this case a CAM) recently. CAMs are transmitted over GeoNetworking packets only consisting of the Common Header, which match with Beacon messages' format. As a result, the transmission CAM messages indirectly determines the transmission of Beacons with a higher frequency compared to that at which beacons would be initially broadcasted.

The Decentralized Environmental Notification Basic Service [36] is mainly used to support road hazard warning applications (Table 2-1). If a given road hazard warning application detects a dangerous situation on the road (e.g. a stationary vehicle following an accident), it uses this service to generate Decentralized Environmental Notification Messages (DENMs) aimed at immediately alerting other vehicles about the detected event. The transmission of DENM messages takes place using GeoBroadcast packets addressed to a geographical area containing vehicles that may be concerned by the dangerous situation. The DENM message has to be regenerated with a given frequency as long as the dangerous event persists. On receiving nodes, the information contained in DENM messages is processed at Facilities level in order for the running application to decide whether it is relevant or not, and eventually react. Based on the critical nature of the supported road hazard warning applications, DENM messages are forwarded and disseminated over relatively limited areas (the surrounding of the detected dangerous event). Moreover, DENM transmissions are required to respect strict latency requirements, which may imply generating such notification messages with high frequencies (up to 10Hz according to [26]).

2.7 Summary and discussion

The strict requirements of cooperative applications and the important challenges of vehicular communications have driven the generation of international standards for communications in ITS environments. These standards specify complete architectures and communication stacks for the execution cooperative applications. With a particular focus on European standards, this chapter has described the most important architectural components enabling routing and dissemination protocols. Particular attention has been given to the IEEE 802.11p/ETSI ITS G5 standards and the ETSI ITSC GeoNetworking stack. 802.11p/ITS G5 is an evolution of the IEEE 802.11a standard operating at 5GHz frequency band. By transmitting on 10MHz channels and adopting longer guard intervals, it can better handle the effects of multipath delay spread and allow reliable V2V and V2I transmissions. Moreover, thanks to the adoption of the IEEE 802.11e's EDCA mechanism, the 802.11p/ITS G5 can differentiate data traffic based on its QoS requirements. Fast vehicular communications over 802.11p/ITS G5 are possible thanks to the suppression of IEEE 802.11's association and authentication mechanisms to join BSSs or IBSSs. The ETSI ITSC GeoNetworking stack defines and implements all the needed functionalities to enable effective multi-hop transmissions based on the knowledge of node positions. Vehicles and RSUs inform neighbouring nodes about their positions by broadcasting periodic Beacon messages. Various transmission modes including GeoUnicast, GeoAnycast, GeoBroadcast, and TopoBroadcast are specified by the GeoNetworking stack. GeoNetworking transmissions are particularly useful in situations of increased mobility as typically occurs in vehicular communication environments. In these situations, continuous topological changes in the VANET compromise the possibility of using traditional ad-hoc routing schemes. Moreover, GeoNetworking transmissions permit executing cooperative applications addressing messages to destination nodes placed on specific areas. These areas are generally selected based on the relevance that the transmitted information has over them.

3

Vehicular Routing and Dissemination

Many cooperative ITS applications will need to transfer information to distant nodes or geographical areas where it can have a practical utility for drivers. Over the destination area, this information has to be properly distributed to maximize the message reception probability. In this way, the highest number of drivers can analyze the information and react accordingly. Transferring information to distant nodes or areas with vehicular short-range ad-hoc radio technology implies the use of multi-hop communications. In this context, multi-hop routing protocols are necessary to determine reliable routes of forwarding vehicles connecting source to destination nodes. In addition, dissemination strategies are needed to optimally distribute the transmitted messages to possibly interested vehicles. The design of vehicular routing and dissemination protocols is not an easy task, as it has to face the challenging vehicular communication characteristics. In the following, an overview of the state of the art on vehicular routing and dissemination protocols is outlined. This analysis permits understanding the motivations behind designing the novel routing and dissemination approaches presented in this thesis.

Section 3.1 introduces some representative examples of cooperative applications requiring routing and dissemination protocols. Based on these examples, it defines routing and dissemination protocols for vehicular communication environments and discusses the main challenges that need to be addressed by these protocols. Section 3.2 and 3.3 give an overview of the most significant vehicular routing and dissemination protocols proposed in the literature. Section 3.4 concludes the chapter with a summary and some discussions.

3.1 Introduction

The previous chapter has described how the implementation of many cooperative ITS applications will be possible thanks to the adoption of specific vehicular ad-hoc communication and networking technologies. The use of radio interfaces like IEEE 802.11p/ETSI ITS G5 on vehicles driving throughout the road network will enable communications over VANETs. VANETs will permit transferring relevant information to vehicles that can obtain a practical utility out of it. The scenario depicted in Figure 3-1 depicts a situation in which a road accident is starting to cause traffic congestion. A real time notification of this event would interest different categories of vehicles for distinct reasons depending on their positions with respect to the event. All the vehicles in the close proximities of the accident have to be immediately warned about this dangerous situation. As described in Section 2.6, this can be done by a road hazard warning application triggering the transmission of DENM messages. DENM messages are immediately broadcasted by the first vehicle detecting the risk (e.g. the vehicle that suffered the accident). The payload of DENM messages carries specifications on the geographical zone over which vehicles have to be warned to ensure the safety of their passengers ("traffic safety relevance area" in Figure 3-1). By analyzing this information, vehicles receiving the messages can decide whether rebroadcasting the message or not according to the requirement of disseminating the warning to all the possible receivers in the safety relevance area. The DENM should be broadcasted periodically as long as the situation that generated its creation persists. However, its usefulness in the close surrounding of the accident diminishes a few seconds after its first transmissions. In fact, many of the vehicles that successfully received a DENM avoided further collisions but could not prevent from being involved in a traffic jam. What is desirable in these situations is transferring the event notification towards distant zones of the road network. Vehicles receiving the notification would have enough time to plan new routes, take alternative directions to bypass the traffic jam, and hence contribute to increase the overall traffic fluidity. A way to achieve this objective could be adopting a cooperative traffic efficiency application aimed at notifying the event over specific "traffic efficiency relevance areas" (see Figure 3-1). By knowing the usual traffic flow directions, the application could strategically select these areas as the most concerned by the traffic jam. As the figure shows, such areas would be far enough from the problematic event to permit vehicles to take individual rerouting decisions or implement common itinerary changes.

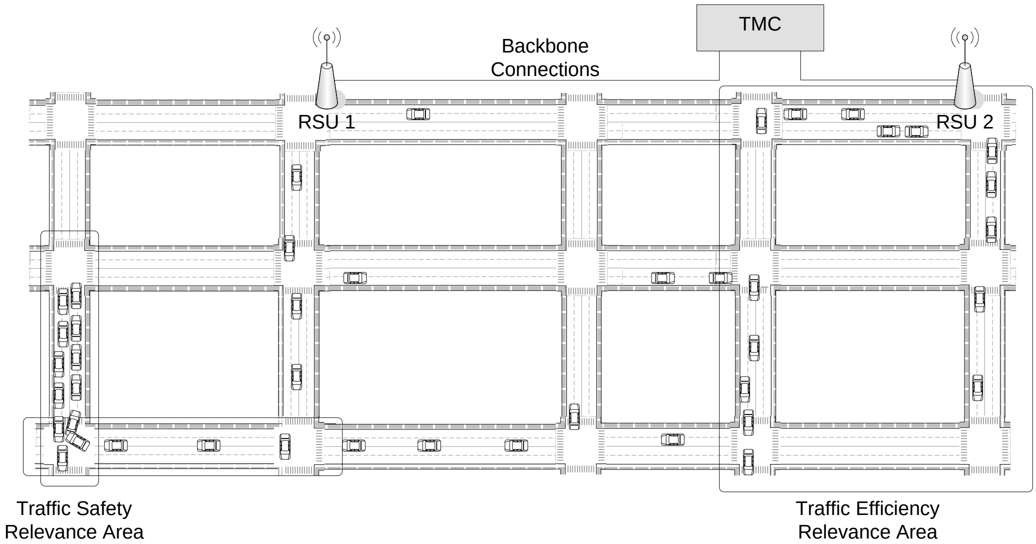


Figure 3-1. Example of scenario for vehicular routing and dissemination.

To reach distant areas through vehicular ad-hoc networks, cooperative applications have to rely on multi-hop transmissions. Multi-hop transmissions could transfer the notification message from vehicle to vehicle directly to the targeted relevance area. Alternatively (and wherever possible), they could address RSUs connected to a centralized Traffic Management Center (TMC). The TMC could analyze the received information and further characterize the notification before relying it (e.g. suggesting new routes for the vehicles in the addressed relevance areas). Messages from the TMC to the relevance areas could be transmitted using one of the communication technologies admitted by the ETSI ITSC architecture. In the scenario depicted in Figure 3-1, the TMC is connected with a RSU placed within the relevance area, so the messages could be relayed through this RSU to passing-by vehicles. However, the TMC could exploit other communication technologies (e.g. cellular networks or broadcasting systems) for the same purpose. Over the relevance area, traffic information messages must be properly distributed to the highest possible amount of recipient vehicles: the more vehicles are correctly informed about the traffic congestion, the more of them will be able to avoid it. For this purpose, V2I and V2V communications can be useful.

The implementation, effectiveness and efficiency of the described cooperative applications depend on the adopted routing and dissemination protocols. In the context of wireless ad-hoc networks, a routing protocol determines routes of forwarding nodes that a given source has to adopt to communicate with a destination through multi-hop transmissions. Routing protocols can be classified according to the considered type of destination. Unicast routing protocols are adopted when the destination is a single node.

Broadcast and multicast protocols are employed to address respectively the totality of possible destination nodes, or only a specific part of them. In this thesis, the term “routing” refers to situations in which the destination is a single node (e.g. a single vehicle or RSU). This permits a clear differentiation between routing protocols and dissemination protocols. Differently from a routing protocol, a dissemination protocol is a networking mechanism through which relevant information is distributed to a set of interested nodes. This thesis considers vehicular routing and dissemination of messages without critical reception latency requirements. Cooperative applications using this kind of messages are for instance traffic efficiency applications. Taking as example Figure 3-1, vehicular routing protocols would be used to route notification messages to specific destination nodes (e.g. one of the vehicles in the traffic efficiency relevance area or a RSU that could forward notifications to the TMC). In addition, dissemination protocols would be adopted to properly distribute these notifications to the vehicles in the traffic efficiency relevance area.

The design of vehicular routing and dissemination protocols is not a trivial task, as they have to face the challenges posed by vehicular communication environments. As introduced in Section 2.2 important challenges are the vehicular mobility and the difficult propagation conditions on the adopted 5.9GHz frequency band. In addition, vehicular routing and dissemination protocols have to properly react to situations of both low and high vehicular density. From the one hand, they have to maintain delivery performance when a scarce presence of forwarding vehicles impairs the capability to perform end-to-end multi-hop transmissions. From the other hand, they have to carefully administrate radio transmissions to avoid congesting the radio channel whenever a high number of vehicles is concurrently executing cooperative applications.

3.2 Vehicular routing protocols

VANETs can be seen as a particular type of wireless ad-hoc network where the communicating nodes are vehicles and, possibly, RSUs. Over a wireless ad-hoc network, routes can be calculated using either topology-based or position-based (also known as GeoNetworking or GeoRouting) approaches. Topology-based protocols can be defined as routing schemes in which nodes achieve a (total or partial) knowledge of the network topology that is used for routes computation. On the contrary, in position-based approaches no topology awareness is needed. Subsequent forwarders are dynamically selected at each hop during the data forwarding process. For the selection of the next hop, the geographical position of the destination, as well of those of neighbour nodes, are used.

3.2.1 Topology-based and position-based routing

Two main types of topology-based routing protocols are defined for wireless ad-hoc networks: proactive and reactive protocols. Both proactive and reactive protocols make use of routing tables. Every network node maintains a routing table storing the routes that have to be used to transmit packets towards a given destination. The main difference between proactive and reactive protocols consists in the way routing tables are computed and maintained. Proactive protocols such as OLSR (Optimized Link State Routing) [37] are based on a continuous exchange of control messages that helps nodes to achieve an up-to-date knowledge of the network topology. A node regularly checks the connectivity status of the radio links towards its direct neighbours. At regular periods, or when detecting connectivity changes, it informs the rest of the nodes about the status of its links. Generally, this is done by flooding the network with dedicated messages. By analyzing these messages, each node can compute and update a local vision of the network topology. In turn, this topology is used to calculate the forwarding routes and update routing tables. Following this approach, the control traffic needed to maintain the routing tables up-to-date is significant. For this reason, the adoption of proactive routing protocols only when source data packets are transmitted frequently throughout the network. Moreover, the channel efficiency of proactive protocols highly decreases in case of mobile ad-hoc networks (MANETs). In MANETs, the mobility of nodes determines frequent topology changes that have to be notified with further control messages. When source data traffic is not continuously generated and has to be transmitted in mobile scenarios, the adoption of reactive protocols is preferable. Contrary to proactive protocols, reactive approaches like for example AODV (Ad-hoc On Demand Distance Vector) [38] or DSR (Dynamic Source Routing) [39] calculate and update routes only when data transmissions take place. When a node has to transmit data, it checks its routing table to verify if it holds a route towards the destination. If not, it floods the network with a route request message that is forwarded until reaching the destination. The destination node generates a route reply message that is forwarded back to the source over the shortest path connecting the two nodes. By analyzing these messages, all the nodes involved in the request and reply forwarding learn the routes to source and destination nodes, and update their routing tables accordingly. To react against link failures, reactive protocols assign limited time validity to the computed routes. A route has to be recalculated when it is no longer considered valid. Further route recalculations are triggered when detecting data transmission failures over the adopted routes.

Compared to proactive protocols, reactive approaches fit better with the bandwidth limitation of vehicular networks. They can reduce overhead, especially in scenarios with a limited number of end-to-end data flows. However, a number of studies demonstrated that classical reactive protocols perform poorly when applied in VANETs [40][41]. In fact, the routes calculated by reactive protocols have a very short time validity as a consequence of VANET topology changes. This results in low end-to-end delivery performance, reduced throughput, and increased overhead for route recalculation. As demonstrated in [42], this applies even in very simple scenarios like transmissions of a few hops in highway environments. To solve the limitations of topology-based routing in conditions of high mobility, position-based routing (GeoRouting) approaches can be adopted. This type of protocols does not require that nodes are informed about the network topology. In position-based routing, nodes do not use routing tables to store routes towards individual destinations. On the contrary, they use location tables storing the geographical position of neighbours and destinations. Every node obtains its own position by a GPS device. In addition, the location of neighbor nodes is achieved by continuously receiving broadcast beacon messages (e.g. as described in Section 2.5.2 considering the case of the ETSI ITS GeoNetworking standards). By analyzing the position information contained in their location tables, forwarding nodes dynamically compute routes at subsequent hops. In general, a source node that wants to transmit data to a given destination includes the destination's position in the transmitted packets. Nodes receiving these packets compare the destination's position with their own position and with the position of their neighbours to select the most suitable next forwarder. For example, a node could select the next hop as the neighbour exhibiting the lowest distance to the destination. Thanks to the dynamic selection of forwarders, GeoRouting protocols do not need control messages to reactively calculate or proactively maintain routes. On the contrary, they only request nodes to exchange broadcast beacons. In VANETs, these transmissions are necessary for the implementation of many standard cooperative applications (e.g. CAM messages as explained in Section 2.6). As a result, vehicular GeoRouting protocols are more scalable in the use of the communication channel. Moreover, the dynamic selection of subsequent forwarders permits GeoRouting protocols to better resist to the continuous topological changes of VANETs, and hence results in higher end-to-end delivery performance [43].

3.2.2 Vehicular GeoRouting

In general, GeoRouting protocols adopt the so-called greedy forwarding approach. In greedy forwarding, subsequent forwarders are selected based on their capability to progressively bring transmitted data packets closer to the destination. Basic examples of GeoRouting protocols using this scheme are the Greedy Perimeter Stateless Routing (GPSR) [44] and Contention-Based Forwarding (CBF) [45] protocols, both commonly adopted in traditional Mobile Ad-hoc Networks (MANETs). In GPSR, the current forwarder looks into its location table to find the neighbour having the lowest distance from the destination. Once this neighbour is detected, the data packet is unicast transmitted. On the contrary, in CBF, the data packet is forwarded using broadcast transmissions. Along with the destination's position, the packet carries the position of the current forwarder. By analyzing this information, every receiver can calculate the geographical progress towards the destination. Upon receiving the packet, every receiver activates a timer whose expiration triggers the packet broadcasting. As the duration of this timer is inversely proportional to the provided progress, the closest receiver to the destination rebroadcasts the packet first. The other nodes with the timer active disable their broadcasting attempt when overhearing the forwarded packet.

The GPSR and CBF protocols may suffer the so-called "local maximum" problem. A local maximum occurs every time a packet is forwarded to a node that has no neighbours offering further progress towards the destination. In this case, a protocol may try to recover the packet forwarding by searching alternative routes, or decide to drop the packet, reducing the delivery performance. For instance, GPSR proposes an interesting recovery strategy that forwards the packet along a route surrounding the local maximum in a tangential way. Although effective in classical MANETs, this recovery strategy does not adapt well in VANET scenarios. In such scenarios, store, carry and forward techniques are more suitable. To demonstrate this concept, the authors of [46] presented a modified version of GPSR including a recovery strategy of this type. When a vehicle experiences a situation of local maximum, it caches the packet at the network layer. In the meanwhile, it waits for vehicles' mobility to make the conditions of local maximum disappear. In fact, after some time neighbours may start providing progress towards the destination. In addition, new neighbours providing such progress may be discovered. Reactivating the greedy forwarding to one of these neighbours prevents from dropping the packet. In this way, satisfactory end-to-end delivery levels can be maintained, but at the expense of increased latencies.

The rest of this section reports a classification of the most relevant vehicular GeoRouting protocols at the time of performing this study. The described protocols implement advanced mechanisms to improve the performance of the above-mentioned traditional schemes. The presented classification follows the operational strategy and information that the GeoRouting protocols use to compute their routes.

3.2.2.1 Map-assisted protocols

Previous studies have evaluated how GeoRouting protocols are affected by radio propagation in urban scenarios [47]. In such scenarios, the shielding effect of buildings to radio propagation can "hide" possible forwarders. As a consequence, GeoRouting protocols can not always perform the best forwarding decisions, and suffer situations of local maxima more frequently. The shielding effect of buildings creates further problems to the CBF protocol. This shielding effect, combined with the uncontrolled nature of

CBF’s broadcast transmissions creates parallel forwarding routes that may consume radio resources in a redundant way.

To overcome the discussed inefficiencies, map-assisted protocols have been proposed. Map-assisted GeoRouting protocols apply the greedy forwarding scheme along a geographical path consisting of road segments and intersections between source and destination. For this purpose, the routed packet also contains a list of intermediate anchor points (e.g. intersections) that have to be traversed. Over the geographical forwarding path, the packet is greedy forwarded towards the vehicle having the shortest distance from the center of the next intersection. Once this intersection has been reached, the next one is addressed. Forwarders apply this process until all the intersections listed in the packet have been traversed, and the final destination has been reached. The rationale behind this method is that vehicles at intersections have better radio visibility conditions towards adjacent road sections. As a consequence, they can operate better selections of the next hops, and provide reliability to the greedy forwarding scheme. The Spatially Aware Routing (SAR) [48] and Geographic Source Routing (GSR) [49] are two representative examples of map-assisted GeoRouting protocols. Both of them rely on digital maps representing the road network to define the list of anchor points (intersections) that have to be subsequently addressed to reach the final destination. However, these geographical forwarding paths are computed by simply considering the shortest distance between source and destination. As a consequence, neither SAR or GSR can guarantee the presence of forwarding vehicles along these paths. In addition, these protocols do not provide the possibility to dynamically modify the selected paths if a local maximum is encountered over them. In this context, the Greedy Perimeter Coordinator Routing (GPCR) protocol [50] provides more flexibility. GPCR forwards packets towards vehicles called “coordinator nodes” placed at the intermediate intersections. Differently from the previous approaches, coordinator nodes are assigned the task to select the next forwarding direction (i.e. the next intersection). In this selection, coordinator nodes exclude the adjacent road segments over which they have no neighbours. Although improving the performance of SAR and GSR, GPCR cannot prevent from incurring local maxima after starting to forward in the chosen direction. As a result, it might not always ensure reliable end-to-end transmissions.

3.2.2.2 Vehicular traffic-aware protocols

The study reported in [51] highlights how uneven spatial distribution of the vehicular traffic can affect the end-to-end delivery capability of the above presented map-assisted protocols. The study proposes A-STAR (Anchor based Street and Traffic Aware Routing) [51], an advanced map-assisted GeoRouting approach that selects its geographical forwarding paths as the sets of road segments experiencing the highest vehicular traffic on average. Relaying data packets along paths characterized by a high presence of vehicles increases the probability to perform uninterrupted multi-hop transmissions, and hence benefits packet delivery. To detect such paths, A-STAR proposes the use of digital maps providing information about bus routes. Here, the assumption is made that buses always drive over the most travelled road segments. Later proposals such as VADD (Vehicle-Assisted Data Delivery) [52] and TBD (Trajectory-Based Data Forwarding) [53] improve A-STAR's approach by considering the adoption of GPS devices providing a time variable characterization of the road network's vehicular traffic. This time variable characterization is provided in terms of vehicular density over distinct roads, and is achieved from long-term traffic statistics. By analyzing this time variable information, the protocols can compute the forwarding paths that best adapt to the actual vehicular traffic situation at every instant. Routing packets over these paths can further increase the reliability of end-to-end transmissions.

3.2.2.3 Real time traffic-aware protocols

The previously described protocols compute geographical forwarding paths considering vehicular traffic information obtained using long-term traffic statistics. Although resulting reliable on average, these paths might not always result valid. For example, roads expected to show high vehicular traffic at a given moment might host no vehicle as a consequence of temporary traffic deviations. Other roads not usually travelled might be congested in reaction to unexpected events like accidents. In these cases, the previously mentioned traffic-aware protocols would not adapt their forwarding path computation to the new distributions of vehicular traffic flows. Their forwarding paths might not have sufficient vehicles to forward packets, and might not be capable to guarantee adequate delivery performance.

Proposals like LOUVRE (Landmark Overlays for Urban Vehicular Routing Environments) [54] and RBVT-P (Proactive Road-Based using Vehicular Traffic routing) [55] can handle these situations by making use of real time vehicular traffic information. In these protocols, vehicles assess the real time vehicular density in their local surrounding. Then, they proactively disseminate this information throughout the VANET using periodic broadcast messages. By receiving these messages, vehicles obtain a shared vehicular density map of the road network. This map can be reused to compute geographical forwarding paths ensuring real time end-to-end connectivity. However, in order to keep up-to-date the information about the density of the road network, a considerable amount of overhead might be created. The SADV (Static-node Assisted adaptive Data dissemination protocol for Vehicular networks) proposal [56] solves this problem by routing packets through static nodes placed at each road intersection. Estimations of the delay needed for a packet to be forwarded between two adjacent intersections are disseminated by vehicles. In this way, the protocol can compute up-to-date forwarding paths able to account for instantaneous changes in traffic flow distribution. Despite this adaptive feature, SADV is based on the unrealistic assumption of static nodes deployed at every intersection.

The Improved Greedy Traffic Aware Routing protocol (GyTAR) [57] combines the use of real time traffic information with the dynamic recalculation of forwarding directions proposed by GPCR [50]. Every time a packet is received at a road intersection, GyTAR identifies the next intersection considering two aspects. The first is the progress provided by a candidate intersection towards the final destination. The second is the estimated real time vehicular density along the road segment leading to that intersection. To compute road segments' density, GyTAR adopts IFTIS (Infrastructure-Free Traffic Information System) [58], a fully distributed algorithm using dedicated multi-hop transmissions. Similarly to GyTAR, the Reliable Inter-Vehicular Routing (RIVER) protocol [59] uses dedicated "probe messages" to actively monitor whether the road segments close to the current forwarder allow reliable multi-hop transmissions. In addition, RIVER defines a passive monitoring system through which vehicles also acquire information about the forwarding capabilities of distant road segments. This information is carried in the data packets routed throughout the VANET. The Intersection-based Geographical Routing Protocol (IGRP) [60] complements the estimation of geographical paths' forwarding capability with the QoS requirements of cooperative applications. The proposal makes use of a central control unit that collects mobility information from vehicles and computes in real time optimal forwarding paths. To this aim, it uses genetic algorithms and considers the applications' QoS constraints. The computed paths are then communicated to vehicles on demand using multi-hop transmissions.

As shown in this review, recent GeoRouting vehicular protocols propose adopting real time estimates of the vehicular traffic density to improve the reliability of forwarding decisions. However, obtaining such estimates requires additional transmissions that increase the communications overhead and hence the probability of channel congestion in dense vehicular scenarios. Moreover, forwarding decisions based on vehicular density might result in always routing packets over the road segments most prone to suffer channel congestion.

3.2.2.4 Contention-based forwarding protocols

Most of the discussed protocols adopt a "sender-based" forwarding approach in which packets are unicasted to the node with the highest progress towards the final destination. While this approach can reduce the latency and number of hops to reach the final destination, it automatically tends to increase the distance separating subsequent hops.

This in turn may result in routing data packets over unreliable radio links [61]. This unreliability may increase the overhead due to retransmissions [61], or require additional protocol complexity to characterize the quality of vehicular links [62][63]. In contention-based forwarding schemes, packets are forwarded through broadcast transmissions (e.g. the CBF protocol described in Section 3.2.2). When receiving a packet, nodes activate a distributed contention mechanism to determine the next forwarder. Although contention-based forwarding forces multiple nodes to receive and process the same packet, it also ensures that at least one of them will forward the packet. As a result, it reduces the probability of transmission failures and consequently increases the end-to-end delivery performance.

Due to its broadcast nature, contention-based forwarding in VANETs has been mostly adopted for information dissemination over target areas. However, contention-based forwarding provides considerable advantages for vehicular routing, being CBF the most representative example. As demonstrated in [61], in highway communication scenarios CBF outperforms a basic sender-based greedy forwarding scheme in end-to-end delivery capability as well as in consumption of radio resources. Protocols like CBRP (Contention Based Routing Protocol) [64] and CLA-S (Connection-less Approach for Streets) [65] apply contention-based forwarding in urban environments. Inspired from [56], CBRP assumes that vehicles are informed about reliable forwarding paths by fixed static nodes deployed at every intersection, which is highly unrealistic. On the other hand, CLA-S introduces the concept of "forwarding area" as a set of streets and intersections where the forwarded data packets are intentionally replicated. This replication increases the chances to deliver packets to the final destination, but also the communications load. More recently, the Beacon-less Routing Algorithm for Vehicular Environments (BRAVE) [66] has proposed the adoption of contention-based broadcast transmissions over geographical forwarding paths consisting of subsequent intersections. The set of intersections is computed through the Dijkstra algorithm in order to find the shortest path to the destination. However, no real time estimation of the actual forwarding capability of these paths is considered. To cope with possible disconnections along the selected forwarding paths, BRAVE adopts a store, carry and forward recovery strategy.

3.3 Vehicular dissemination protocols

While vehicular routing implements the functionalities to correctly route data to a given destination, vehicular dissemination is in charge of distributing information to a set of interested vehicles. As previously explained, dissemination protocols can be used to support different kinds of cooperative ITS applications. In most of the cases, they are applied to inform vehicles belonging to specific target areas where the distributed data content is relevant.

In principle, disseminating information in vehicular ITS systems can be performed through any of the wireless technologies admitted by cooperative ITS communication standards (Figure 2-1), as long as technically feasible. However, a given radio access technology has specific characteristics aimed at optimally supporting the communication services it is designed for. As a consequence, a specific communication technology could support some cooperative dissemination applications better than others. As an example, short-range ad-hoc IEEE 802.11p/ETSI ITS G5 radio interfaces would allow instantaneous V2V dissemination of a road-hazard warning in the close surrounding of an accident, but might not always ensure adequate delivery over larger areas. At the same time, communications systems with increased coverage capabilities could better disseminate traffic information over distant or wider areas, but might not always guarantee the delay constraints of certain applications.

Many literature studies propose vehicular dissemination protocols based on the exclusive use of IEEE 802.11p/ETSI ITS G5 communication standards. Accordingly, various reviews on vehicular dissemination protocols only focus on this type of approaches (e.g. [67][68]). The proposed classifications are based on operational aspects characterizing these schemes. In this thesis, a different classification of vehicular dissemination protocols is proposed. This classification takes into account the communication technologies and actors involved in the dissemination process. Three main types of vehicular dissemination protocols are considered. First, approaches that only use ad-hoc V2V communications are described. Then, protocols also exploiting the presence of RSUs are outlined. Finally, hybrid V2X dissemination schemes are analyzed. These schemes combine V2V communications over IEEE 802.11p/ETSI ITS G5 interfaces with I2V (Infrastructure-to-Vehicle) transmissions from traditional infrastructure-based radio technologies (e.g. cellular networks).

3.3.1 V2V protocols

In general, a cooperative ITS application requires message dissemination to distribute information that is not personalized but common for many interested drivers. As a consequence, the use of broadcast transmissions to disseminate this information is the most appropriate. In this context, two main types of dissemination approaches can be identified, namely single-hop and multi-hop broadcasting protocols.

In single-hop broadcasting, vehicles periodically broadcast messages along their routes. The transmitted messages can contain information of different types like for example the locally estimated vehicular density, the presence of risks on the road, or a point of interest notification. Receiving vehicles may decide to store this information and combine it with the information already present in their databases. This allows implementing intelligent dissemination schemes in which each vehicle can continuously monitor its database to check the relevance of the stored information in the current driving situation. If a vehicle considers that this information (or part of it) can be relevant for its neighbours in the current context, it can broadcast a message. Two well representative examples of this dissemination approach are the TrafficView [69] and the SODAD (Segment-oriented Data Abstraction and Dissemination) [70] protocols. The dissemination approach of these protocols fits well with traffic monitoring applications. In fact, through the continuous exchange of relevant information, it can contribute to creating a cooperative and shared vision of the road traffic situation. However, single-hop broadcasting can also be used for disseminating traffic notifications over relevance areas. The study presented in [71] proposes an opportunistic dissemination protocol for traffic notifications. To receive notifications over the relevance area, recipient vehicles have to subscribe to this service. The notification message is replicated in a given number of copies and assigned to an equal number of vehicles called “carriers”. Carriers store the message and carry it along their routes. Periodically, they use broadcast transmissions to poll their neighborhood with the aim of receiving service subscriptions. As long as they receive subscriptions, carriers broadcast the notification message. A similar mechanism based on replication of the notification message and service subscription is adopted by the ACS (Adaptive Copy and Spread) dissemination protocol [72]. Based on the number of received subscriptions and the position of the subscribers, the duty of notification carrier is passed to new vehicles. In this way, the notification message can be carried towards zones containing a high amount of still uninformed vehicles. In addition, when carriers reach the boundary of the relevance area, ACS selects new carriers driving in the opposite direction. In this way, ACS keeps the dissemination of notification messages alive in the relevance area. Similarly to these contributions, [73] proposes an Application-level Role Mobility (ARM) framework supporting single-hop broadcast dissemination. ARM defines distributed mechanisms through which vehicles handover the duty of carrier to maintain message dissemination in a circumscribed target region. In this way, the behavior of a RSU broadcasting from a fixed position is emulated.

Multi-hop broadcasting protocols are generally referred by the literature as the networking mechanisms adopted to rapidly warn vehicles about dangerous situations (i.e. accidents) on the road. As such, these protocols are appropriate to disseminate standard DENM messages [36] (see Section 2.6). However, many of the presented protocols could be adopted by other types of applications with less stringent latency and delivery requirements (e.g. traffic efficiency applications). Various works on V2V multi-hop broadcast dissemination protocols take as case study the notification of road-hazard warnings in highways scenarios [74]-[78]. In these scenarios, the highest challenges derive from situations of high vehicular density. In these situations, all the nodes receiving a broadcast notification are potential rebroadcasters. Therefore, techniques are studied to limit the overall number of transmissions that may create collisions and congest the radio channel, causing the so-called "broadcast storm" problem. These works demonstrate that the broadcast storm problem is critical as it can affect the correct and timely delivery of the notification. Optimal rebroadcasters are selected adopting distributed contention-based schemes that assign different transmission delays [74]-[76] or probabilities [77][78] to distinct receivers. To further improve these schemes, the approach presented in [79] assigns a higher rebroadcasting probability to nodes that are closer to the position of the notified event. This solution aims at increasing the probability of reception in the close surrounding of the event, where the warning is more relevant. Besides this feature, the protocol presented in [79] is also capable to maintain the broadcasting alive in absence of rebroadcasters. When receiving the notification message from a given direction of the highway, a vehicle checks the presence of neighbors in the opposite direction. If no such neighbors are present (i.e. no beacons from this direction have been received recently), the vehicle assumes that the message would not be further broadcasted in this direction. In this case, it stores the message and waits for rebroadcasting it to new neighbors coming from this direction. The work presented in [80] proposes a similar scheme that keeps alive the message dissemination based on rebroadcasting timers that get adapted to the vehicular density experienced by nodes.

Differently from the described proposals, other studies focus on multi-hop dissemination over urban VANETs. One of the first proposals of this type is the Ad-hoc Multi-hop Broadcast (AMB) protocol [81]. AMB uses directional transmissions along the road segments of the considered urban scenario. When reaching a vehicle placed at a road intersection, the packet is replicated in multiple copies. Each of them is rebroadcasted in the direction of one of the adjacent road segments. AMB also proposes the use of V2V broadcast retransmissions and acknowledgments at MAC level (not initially admitted by IEEE 802.11p/ETSI ITS G5) to provide increased reliability to message dissemination. The study presented in [82] proposes RVG (Reliable Vehicular GeoBroadcast), an interesting framework for vehicular multi-hop broadcast dissemination. RVG is composed by various operational blocks. A vehicle that has to broadcast a message runs a "slotted restricted mobility-based" scheme. This scheme detects the most reliable rebroadcasters over different directions through a careful analysis of the movement of neighboring vehicles. Before broadcasting, the vehicle includes the IDs of these rebroadcasters in the message. Among the receivers, the selected rebroadcasters transmit the message first. The rest of vehicles run a "neighbor elimination" scheme according to which they rebroadcast only if detecting neighbors that might have missed the message.

This is done by estimating the area that past transmissions should have covered. Vehicles not initially selected as rebroadcasters also run a "pseudo acknowledgment" scheme. If not overhearing transmissions from the selected rebroadcasters, they rebroadcast the message themselves indicating the ID of the expected rebroadcasters. To provide message dissemination with adequate robustness, the pseudo acknowledgment scheme is periodically repeated until expected broadcast transmissions are overheard. In [83], a very interesting Profile-driven Adaptive Warning Dissemination System (PAWDS) is proposed. The authors demonstrate that dissemination performance strongly depends on the topological features of the considered road network scenario in terms of number of road segments and intersections. Starting from this observation, PADWS dynamically adapts some of its key parameters, such as the interval between consecutive warning notifications and the adopted broadcast scheme, to the features of the road network scenario. Another interesting dissemination protocol is ABSM (Acknowledged Broadcast from Static to highly Mobile) [84]. This protocol includes dedicated information to periodic beacon messages to inform vehicles about already disseminated messages. Each vehicle rebroadcasts a new message according to whether it belongs to a "connected dominating set" of nodes. Connected dominating sets contain vehicles that are mutually connected either directly or through multi-hop transmissions. By giving rebroadcasting priority to vehicles in dominating sets, ABSM increases the dissemination reliability. The Urban Vehicular BroadCAST (UV-CAST) protocol [85] also aims at increasing the reliability of dissemination in urban communication scenarios. It achieves this objective by addressing both the broadcast storm and disconnected network problems. The message to be disseminated is relayed by multi-hop broadcast transmissions as long as the VANET is connected. A contention-based approach is adopted to make vehicles placed at road intersections transmit with higher priority, and hence disseminate towards the adjacent road segments. When a vehicle realizes it is placed at the boundary of a connected set of vehicles, it activates a store, carry and forward mechanism. According to this mechanism, the vehicle rebroadcasts a message only when new neighbours are discovered.

3.3.2 RSU-assisted protocols

V2V dissemination protocols can implement opportunistic carry, store and forward mechanisms to react against possible VANET disconnections caused by a low presence of forwarding nodes. However, the effectiveness of these fully ad-hoc V2V dissemination protocols may be strongly conditioned by a low penetration of 802.11p/ITS G5 radio interfaces on vehicles. This would be particularly the case during the roll-out phase of cooperative ITS systems. To overcome this problem, various studies have proposed dissemination protocols also making use of RSUs.

To demonstrate the added value achieved through the assistance of RSUs, [86] proposes a simple protocol in which RSUs store and rebroadcast notifications received from passing-by vehicles. Similarly, the authors of [87] propose to enrich V2V message dissemination with the use of backbone-interconnected RSUs. In this approach, RSUs can act not only as relay points for inter-vehicle communications, but also as message disseminators. Another similar approach is presented in [88]. In this study, the data disseminated from a source vehicle can be buffered and periodically rebroadcasted by RSUs placed at intersections over the roads normally experiencing the highest vehicular traffic. All these studies demonstrated that considerable improvements in the dissemination delivery and latency performance can be achieved even with a small number of RSUs. The work presented in [89] combines the use of RSUs with the subscription/dissemination mechanism of [71] (Section 3.3.1), and introduces the concept of "home zone". The home zones are strategic points where a notification message has to be disseminated to reach the maximum number of possibly interested vehicles. Various replicas of the notification message are then routed to specific "home zones" where RSUs are in charge of their rebroadcasting. To increase the scope of the dissemination, every vehicle having already received the message can opportunistically rebroadcast it in presence of message subscribers.

Given the benefits that RSUs can provide to message dissemination, other works have investigated RSU deployment strategies to optimize dissemination performance. For instance, [90] formulates a problem that allows determining where a given number of RSUs have to be placed to maximize the amount of vehicles that get in contact with them. As a subsequent step, the problem is reformulated to obtain the RSU placement permitting vehicles to remain in contact with RSUs for a specific period.

3.3.3 Hybrid V2X protocols

In the previous sections, it has been explained how store, carry and forward techniques or the prospective presence of interconnected RSUs can mitigate the negative effects of VANET disconnections on the performance of vehicular dissemination. However, further countermeasures might be needed to overcome the problem of disconnections in urban road network scenarios. In these scenarios, VANET disconnections can be generated by uneven distributions of traffic flows and by the obstructing effect of large-sized obstacles (e.g. buildings) to radio propagation. As demonstrated in [84] and [91], VANETs disconnections influence the reliability of vehicular dissemination and may provoke suboptimal delivery over the relevance area. Vehicles in some zones could correctly receive the disseminated messages. However, other vehicles in distinct areas might receive messages with increased latencies or miss them completely. To obtain a more uniform dissemination over the relevance area, communication technologies with extended coverage capabilities (3G/4G cellular networks, WIMAX, or even DVB broadcasting systems) could be adopted [92]. In this context, recent studies have proposed hybrid V2X dissemination strategies combining I2V transmissions from traditional infrastructure-based radio technologies (e.g. cellular networks) with V2V communications over VANETs. Through this approach, a few copies of the message can be transmitted to vehicles placed in distinct and possibly disconnected zones of the relevance area using I2V transmissions. The vehicles receiving these messages can start to cooperatively disseminate in the VANET using V2V communications. If adequately designed, this approach can allow disseminating messages effectively and efficiently.

Hybrid V2X dissemination approaches have been investigated in a very limited number of studies. The authors of [93] propose STEID (Spatio-Temporal Emergency Information Dissemination), an emergency dissemination protocol based on a hybrid architecture linking "clusters" of vehicles through cellular links. STEID defines clusters as sets of vehicles that can communicate through direct or multi-hop V2V transmissions. To permit that a notification originated in a given cluster is disseminated in a separate cluster, cellular transmissions are used. In [94], the authors propose LTE4V2X, a centralized framework for the formation of clusters of vehicles. Based on the information that each vehicle uploads via cellular networks, a centralized Traffic Management Center (TMC) computes a "cluster topology" that is the set of clusters that are expected to be stable and ensure reliable intra-cluster V2V transmissions. The cluster topology is transmitted to vehicles using the cellular downlink channel. This topology is then used for information collection and dissemination purposes. A similar hybrid architecture including clusters of vehicles and cellular transmissions is used in [95] to investigate situations in which vehicles may not initially want to cooperate in the dissemination of messages. To give vehicles an incentive, the authors propose a solution based on the coalition game theory. In [96], a "cross-network information dissemination" approach is presented. A TMC uses the UMTS network to inject alert messages to a reduced amount of vehicles referred to as "gateways". The UMTS network is also used to collect vehicular traffic data. By centrally analyzing this data, the vehicular traffic density can be estimated. These estimates are then communicated to gateway nodes. Gateway nodes use the received estimates to optimize the parameters of the multi-hop broadcasting protocols used to disseminate alert messages in the VANET. Differently from the previous schemes, Push & Track [91] aims at delivering messages to all the vehicles in a relevance area by a service-dependent expiration deadline. Like in [96], messages are generated by a centralized entity that relies on the UMTS network to inject message copies to specific vehicles. Once received in the VANET, message copies are forwarded using opportunistic V2V communications. The particularity of Push & Track is the feedback loop through which the centralized entity receives message receptions acknowledgements by vehicles through UMTS uplink transmissions. With these acknowledgements, the centralized entity can compute how many message copies have still to be injected and to which vehicles. As demonstrated in [91], this hybrid V2X dissemination scheme achieves the highest delivery performance whenever the injection is guided by a VANET's V2V connectivity characterization. A global V2V connectivity picture can be achieved out of vehicular information collected from the VANET through the cellular uplink channels. However, building this global picture requires a good characterization of the VANET's multi-hop forwarding capabilities. Moreover, the collection protocols used for this purpose do not have to overload the cellular channels.

3.4 Summary and discussion

This chapter has presented an overview of relevant vehicular routing and dissemination protocols in the context of this thesis. The review has shown that GeoRouting protocols are the most suitable to react to the topology changes expected in vehicular networks. GeoRouting proposals have evolved towards schemes applying greedy forwarding over reliable geographical paths composed by highly travelled roads. To determine these paths in real time, estimations of the vehicular density are generally employed. These estimations are obtained using V2V-based distributed protocols. However, estimating vehicular density in a distributed way may result in a significant communications overhead. In addition, most of the presented routing schemes route the packets using the sender-based forwarding approach. Compared to contention-based forwarding, this approach can reduce the latency, but might result in transmitting over unreliable radio links, and negatively affect delivery capability.

Vehicular dissemination protocols generally rely on single-hop or multi-hop V2V broadcast transmissions to deliver information to a large amount of vehicles. Various schemes have been proposed to avoid flooding the network with redundant transmissions in high vehicular density scenarios. Other methods ensure information dissemination persistence in case of VANET disconnections. The use of RSUs has been identified as a promising solution to support message dissemination in case of scarce presence of forwarding vehicles, or during the roll-out phase of vehicular networks. However, relying only on multi-hop vehicular communications might not always ensure the necessary reliability. The use of hybrid V2X communications exploiting complementary radio access technologies can solve this inefficiency. However, communication technologies other than IEEE 802.11p/ETSI ITS G5 have not initially been designed to support cooperative ITS services. Therefore, their radio channels should be carefully managed when implementing cooperative ITS applications.

4

Evaluation Environment

The evaluation methodology of the routing and dissemination protocols proposed in this thesis has to fulfill various requirements. A good evaluation method has to be capable to provide accurate results that could validate the real world applicability of the proposed protocols. For the same reason, an evaluation method should be sufficiently flexible in allowing testing under different scenarios and with varying operational configurations. When considering evaluations of vehicular communication protocols, a very important requirement is the capability to support large scale assessments. In fact, such protocols may implicitly involve the concurrent operation of many nodes over large areas. Repeatability of the experiments is also required. Results must be repeatable and reproducible with the same operational conditions to fairly compare the proposed protocols to existing benchmark schemes. Computer simulation provides an adequate compromise between accuracy, scalability, and experiments' repeatability. In addition, it presents a good flexibility in setting up different evaluation scenarios. For these reasons, it has been chosen as the evaluation method for the protocols presented in this thesis. To guarantee valid and accurate simulation results while leveraging large scale and standard compliant evaluations, this thesis has adopted the iTETRIS integrated wireless communications and traffic simulation platform [97]. By using this simulation tool, the performance and operation of the presented protocols can be easily assessed under realistic evaluation conditions.

This chapter is organized in the following way. Section 4.1 better justifies the suitability of computer simulations for the evaluations required in this thesis. Section 4.2 describes the currently available simulation testbeds for cooperative ITS communications and applications. In Section 4.3, an overview of the iTETRIS simulation tool adopted in this thesis is presented. The wireless communications simulation platform implemented in iTETRIS is described in detail In Section 4.4. Finally, Section 4.5 concludes the chapter by providing a brief summary and some discussions.

4.1 Introduction

The evaluation of cooperative ITS systems, applications and protocols can be performed by various methods. Analytical methods make use of mathematical models. They are adopted to derive closed-form expressions describing performance indicators as a function of configurable operational parameters and working conditions. System performance and theoretical bounds can be immediately computed with analytical methods. Nevertheless, it is very difficult to trustfully reproduce with mathematical models the large amount of real world phenomena, operational conditions, and complex scenarios characterizing vehicular communications. Examples of such investigations (only to cite a few) are presented in [99]-[102]. These studies focus on modelling common VANET properties such as inter-vehicle connectivity, channel occupancy, or channel busy ratio. As it can be observed in these studies, deriving mathematical models often requires adopting simplified assumptions to make the considered problems tractable. Such assumptions may concern vehicles' mobility (e.g. one-dimensional movement, constant speeds, etc.) and/or communications features (e.g. fixed communications range, absence of packet collisions at MAC level, etc). As a result, the outcomes of analytical evaluation methods always require validations (through real world experiments or simulations) that could confirm their correctness and reusability. The assumptions made by analytical methods may be correct in specific situations, and wrong in some others. Therefore, analytical methods show reduced flexibility.

Field Operational Tests (FOTs) involve real communication devices and drivers to evaluate cooperative ITS systems in real world environments. Due to these characteristics, FOTs are being used in various international research initiatives to validate the technical feasibility of cooperative systems and applications. FOTs are also used to investigate the impact of cooperative ITS systems on drivers' behaviour, and to retrieve the first insights on their the costs and benefits [18][22][25]. Despite the high level of accuracy provided, FOTs can be limited in the number of the communicating actors involved in their experimentations (vehicles and base stations). Logistic limitations and economical constraints can also prevent the employment of FOTs for extended experimentation time periods, and on large testing areas. In addition, these limitations might complicate the reproducibility of the experiments with different settings and operational conditions. The fact that FOTs take place in real scenarios where environmental variations are often uncontrollable can also compromise the repeatability of experiments.

In this context, computer simulation has been established over the years as the most commonly used evaluation method for cooperative ITS applications and protocols. In general, a simulation is aimed at modelling on a computer situations that would be difficult to reproduce, study and evaluate in the reality. Computer simulation can efficiently integrate complex mathematical models and manage large amounts of data, thereby better addressing the scalability issues presented by FOTs. Simulations can generate a number of evaluation scenarios with different working conditions, as well as reproduce identical environmental situations for subsequent tests. As a result, simulation is the method that provides the highest flexibility and repeatability of the conducted experiments. However, a key issue in simulation studies is the use of realistic models that could ensure valid and trustful outcomes and conclusions. This is particularly the case for simulations of cooperative ITS applications and communication protocols. Using inaccurate wireless communications and vehicular traffic models highly influences the results of these simulations. For this reason, extensively validated communications and traffic simulation platforms have to be used.

Figure 4-1 summarizes the above mentioned considerations and compares the three presented evaluation methods considering the criteria of modelling accuracy, scalability, flexibility in emulating distinct evaluation scenarios, and capability to support experiments' repeatability. Since this thesis focuses on vehicular routing and dissemination protocols, the evaluation cannot disregards large scale analysis involving large areas and a high number of nodes. Moreover, realistic, flexible, and easily reconfigurable evaluations are needed to verify the applicability of these protocols in different real world scenarios. In addition, repeatability of the experiments is a key issue given that a fair comparison with other protocols is necessary. As it can be noticed in Figure 4-1, only simulation offers a good tradeoff between all these features. For this reason, simulation has been chosen for the evaluations presented in this thesis. However, simulation of vehicular communication protocols might be required to balance scalability and modelling accuracy. Precisely modelling all the aspects of wireless communications may imply very high computational resources and simulation times, especially when simulating a very large number of communicating nodes. To solve this issue, adequate implementation and modelling choices might be necessary.

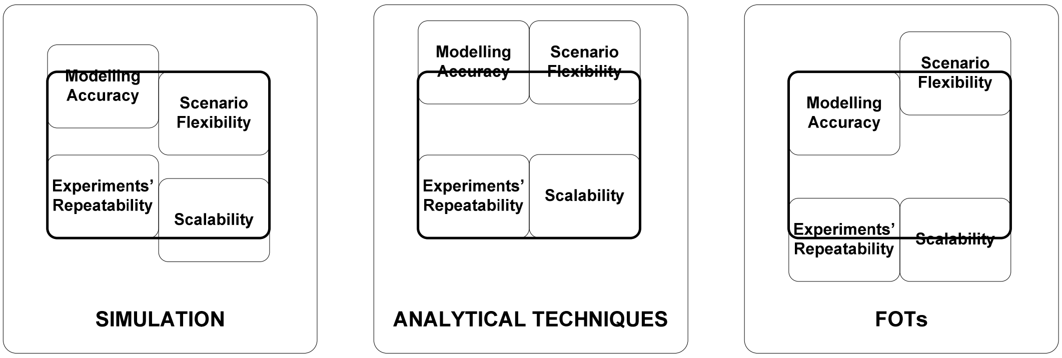


Figure 4-1. Features of the evaluation methods for cooperative applications and protocols.

4.2 Cooperative ITS simulation platforms

The vehicular routing and dissemination protocols presented in this thesis have been implemented and evaluated using the iTETRIS (Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions) simulation platform [97]. iTETRIS is an open source platform combining wireless communications and vehicular mobility simulation capabilities. Traditionally, due to the different nature and research objectives, models for wireless communications and vehicular mobility are developed and used by dedicated simulation platforms. Wireless communications platforms implement protocols, applications, and radio propagation models, while vehicular mobility platforms emulate vehicles' movement, traffic demands, and road network scenarios. For the simulation of cooperative ITS systems and protocols, emulating the dependence between these communications and mobility models is key. In fact, the vehicles' movement might be influenced by the reception of wireless messages, and such receptions highly depend on the positions of sender and receiver nodes. Moreover, mobility and wireless models have to be highly accurate, given that inadequately modelling one of these two aspects may have strong repercussions in the validity of the simulation results [47][103][104]. Given the rising interest of cooperative ITS systems, different initiatives have tried to combine wireless communications and vehicular mobility simulators to enable reliable and accurate evaluations. The resulting cooperative ITS simulation platforms can be classified according to the features of the combined components and adopted integration methods. In the following, a brief list of these platforms is outlined. This permits better understanding the validity and potential of these solutions, and the choice of the simulation platform used in this thesis. Before outlining this list, the wireless communications and vehicular mobility simulation platforms commonly used for integration are described.

4.2.1 Wireless communications simulation platforms

Various simulation platforms are nowadays available for research in communication networks. Many reasons determine the success and adoption of a given platform in the research community. Desirable features are certainly the completeness of implemented communication protocols, the accuracy of the adopted models, the facility in setting-up and reconfigure simulations, the efficiency in administrating the available computational resources, and the effectiveness in limiting simulation execution times. Besides all these characteristics, the support that a platform receives by its developers is a very important factor. Platforms generated from extensive dedicated projects exploit the contribution of expert developers and provide a large number of protocols. The accuracy and validity of such implementations is continuously tested and validated, and their updating is usually ensured for long time periods. Another key feature is the source code availability. If the code of a platform is open source, users can extend the implemented modules with new features and capabilities. Open source simulation platforms provide flexibility in adapting simulation capabilities to personal research interests. Moreover, they foster further improvements and validations of the implemented models thanks to their adoption within large-sized user communities. A (non-exhaustive) list of currently available wireless communications simulators is presented in Table 4-1. As the table shows, despite many platforms can be used for generic wireless simulations, only a limited subset jointly offers enduring and stable support from a large community of users, computational and time efficiency, and capability to be freely extended with new features. These characteristics are strictly necessary to support the implementation and realistic evaluation of communication protocols like those proposed in this thesis.

Platform	Description
ns-2 [105]	Developed by the Lawrence Berkeley National Laboratory and other centers through various research programs (first release in 1996). Main features: discrete-event simulation; very high number of implemented modules and communication protocols; very wide adoption in the research community. Drawbacks: limited scalability and modularity [106]; necessity of using OTcl scripts to configure the simulation (e.g. the network topology).

Platform	Description
ns-3 [107]	Developed by the University of Washington and others research centers through a U.S. National Science Foundation program (first release in June 2008). Main features: network simulation totally implementable in C++; improves ns-2's scalability [108][109]; modularity; coding style and documentation; support for multi-communication technology and multi-channel emulation; open source. Drawbacks: still not complete as ns-2; lack of backward compatibility with ns-2.
OMNeT++ [110]	Developed by the Technical University of Budapest (first release in 1997). Main features: general purpose discrete-event simulator to evaluate large scale scenarios; fully modular; simulations reconfigurable at runtime; open source for academic and non-profit use; GUI support. Drawbacks: not specifically designed for network simulations; wireless modules developed in different OMNET frameworks; limited model library; necessity of using the NED language for simulation configuration; lower simulation performance compared to ns-3 [109].
NCTUns [111]	Developed by the NSL laboratory of the National Chiao Tung University of Taiwan (first release in 2002). Main features: distributed concurrent simulations; includes vehicular traffic models and 802.11p and 1609 modules; open source; GUI support. Drawbacks: lower support and adoption in the user community.
SWANS/JiST [112]	Developed by the Cornell University (first release in April 2004). Main features: implementation of network simulations in standard Java; support for parallel execution of code at different simulation entities, with potential performance gains; open source for academic and non-profit use. Drawbacks: official development no longer supported; higher memory usage compared to ns-3 and OMNET++ [109].
OPNET [113]	Developed by OPNET Technologies Inc. (company created in 1986). Main features: modular scalable wireless simulations incorporating terrain, mobility, and multiple pathloss models; grid computing support for distributed simulation; GUI support; extensive protocol libraries. Drawbacks: not open source; commercial license needed; model files encrypted.
QualNet [114]	Developed by Scalable Network Technologies (company created in 1999). Main features: modelling and simulation tool for wired and wireless networks based on the GlomoSim simulator [115]; exploits multi-threading capabilities of multi-core 64-bit processors; real time speed; scalable of up to thousands of network nodes; GUI support; extensive protocol libraries. Drawbacks: not open source; commercial license needed; model files encrypted.

Table 4-1. Comparison of wireless communications simulators.

4.2.2 Vehicular mobility simulation platforms

Vehicular mobility simulation platforms are commonly referred to as traffic simulators. These simulators are used to plan, implement and evaluate transportation systems and traffic management methods, such as traffic light schedules and other traffic control policies. The precision of the implemented mobility models highly depends on the capability to accurately emulate real road network scenarios, traffic demands, and human driving behaviour. In this context, a classification of mobility models can be made according to the scale by which traffic phenomena are represented and treated. Macroscopic models describe road traffic as vehicle streams and adopt aggregated metrics such as average velocity or turn rates. On the contrary, microscopic models describe the behaviour of every single vehicle, and emulate interactions with other vehicles and the surrounding road network. As an example, car following models are microscopic models that adapt the speed of each vehicle based on that of the preceding vehicles. Recently, vehicular mobility simulators have become popular in the wireless communications research community due to their adoption in the study of VANETs. In fact, a number of traffic simulators are capable to feed wireless communications simulators with mobility traces describing vehicles' positions over the time. In this context, the features asked to traffic simulators are basically the same as expressed in the previous section for wireless communications simulators, with modelling precision and extensibility the most important ones. In general, commercial solutions provide very high modelling accuracy, an extensive number of modules to emulate real-world mobility phenomena, and an easy approach to end users. Anyways, their code is not open source, which complicates its usability in other research domains like vehicular communications. For this purpose, open source simulators are preferred. To better understand the motivations of this preference, Table 4-2 lists the most representative traffic simulators supporting the research on VANETs.

Platform	Description
SUMO [116][117]	Developed by the Institute of Transportation Systems at the German Aerospace Center (first release in 2002). Main features: microscopic, space-continuous and time-discrete simulator; models for different vehicle types, car-following and lane changing; possibility to import real road network topologies from various formats; open source; extensive adoption in both vehicular traffic and wireless communications research community. Drawbacks: slightly lower accuracy compared to commercial solutions.

Platform	Description
VanetMobiSim [118][119]	Developed by Eurecom and other research centers (first release in 2006). Main features: vehicular extension of CanuMobiSim mobility model [120]; support for microscopic and macroscopic simulations; support for real maps, car-following and lane changing models; traffic lights modelling; open source. Drawbacks: lower support and completeness compared to SUMO.
CORSIM [121]	Developed at the McTrans Center of the University of Florida (created in 1986) Main features: improved microscopic simulation logic including lane changing, spillback checking, diagonal movements, complex intersection modelling, freeway acceleration and deceleration lanes, ramp meters; emulation of common traffic controllers such as traffic signs and traffic lights; GUI support. Drawbacks: complexity of calibration; not open source; commercial license needed.
VISSIM [122]	Developed by PTV AG (company created in 1979). Main features: efficient road network editing through graphical editor or background images; sophisticated microscopic modelling based on the Wiedemann car-following model; highly-detailed modelling of intersections; detailed analysis options; improved output file analysis compared to CORSIM; GUI support. Drawbacks: complexity of calibration; not open source; commercial license needed.

Table 4-2. Comparison of traffic simulators used to support research in VANETs.

4.2.3 Integrated simulation platforms

Several studies have developed integrated wireless communications and traffic simulation platforms with varying degrees of integration and modelling accuracy. A schematic representation of the various integration approaches is depicted in Figure 4-2. For example, MoVES [123] presents a framework for parallel and distributed simulations. It is based on a modular and layered modelling of both vehicular and wireless scenarios integrated with mobile applications. AutoMesh [124] includes a set of modules representing driving behaviour and radio propagation, and connects them in a control loop able to reproduce their mutual influence. By using three-dimensional maps and digital elevation models, it is able to realistically reproduce radio propagation effects in urban areas. The VANET simulator [125] models the transmission and reception of wireless messages and vehicle GPS position updates as a series of discrete events. These events are tied by mutual relationships ensuring the generation of new events upon their continuous execution. The GrooveSim tool [126] includes various modular mobility, trip, traffic density, and communications models. In addition, it presents interesting features like visual playback of driving logs, and support for simulations integrating real vehicular communication devices and simulated vehicles. MoVES, AutoMesh, VANET and GrooveSim do not rely on other existing simulation platforms. On the contrary, they present their own implementations of wireless and mobility models that are integrated to form embedded simulation tools (Figure 4-2a). However, studies such as [111] and [118] claim that these tools lack extensive use and testing compared to commercial solutions, or platforms generated in open source projects exploiting the contribution of a large amount of users.

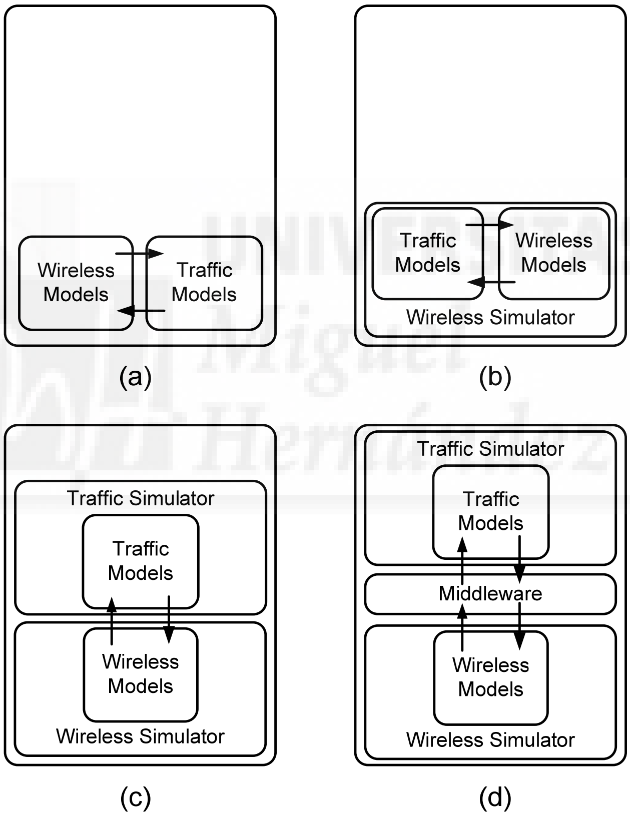


Figure 4-2. Different approaches for integrated cooperative ITS simulation platforms.

To improve realism and modelling accuracy in the study of cooperative ITS systems, works like [111] and [127]-[129] propose to embed vehicular mobility models into validated wireless simulators (Figure 4-2b). [127] embeds into SWANS the Street Random Waypoint (STRAW) tool, which is able to parse real street map data and model complex intersection management policies. [128] presents a collection of SWANS modules, called ASH (Application-aware SWANS with Highway mobility), to model customizable highway topologies, car-following and lane changing models, as well as inter-vehicle geocast data dissemination protocols. Using a similar approach, the network simulator NCTUns [111] incorporates from its version 5.0 the support for road network construction and microscopic vehicle mobility models in a tight coupling with its wireless simulation. Finally, [129] extends the ns-3 network simulator with a set of classes to realistically emulate the behaviour of vehicles over highway scenarios including lane changing and car following models. However, these embedded integrated solutions require users and developers to have knowledge of the wireless communications simulation platforms, and can result in certain difficulties to evolve their code or replace certain modules.

A different integration approach is the direct coupling of separated traffic and wireless simulation platforms (Figure 4-2c). This approach was adopted in [130] using CORSIM and QualNet, and in [131] using VISSIM and ns-2. However, QualNet, CORSIM and VISSIM are commercial platforms that, although ensuring higher modelling accuracy, provide less freedom to integrate new cooperative ITS features. To solve this issue, various solutions were proposed combining two independent open source traffic and wireless simulators [132]-[134]. Chronologically, the first approach in this sense was TraNS [132] integrating SUMO and ns-2, but nowadays its development is no longer supported. More recently, the same fully open source approach has been adopted by Veins (Vehicles in network simulations) [133] combining OMNET++ with SUMO. To allow interaction, Veins implements modules over both the interconnected simulators, with a manager entity in OMNET++ sending commands to SUMO. These commands are used to impose events in the traffic simulation (e.g. change the driving behaviour of a vehicle after a wireless message reception), or to receive updates from the traffic simulation at regular time steps (e.g. new vehicles' positions). The Online Vehicular Network Integrated Simulation (OVNIS) platform [134] combines SUMO with ns-3, and includes an ns-3 module implementing user-defined cooperative ITS applications. In OVNIS, ns-3 is extended to be a "traffic aware network manager". In this approach, ns-3 is not only able to simulate wireless transmissions between vehicles according to the positions retrieved by SUMO. Instead, it can also manage the whole simulation process by controlling interactions between the connected simulators. TraNS, Veins and OVNIS present very interesting approaches but share a non-negligible limitation: by assigning the simulation control to a manager entity that is included in one of the coupled simulators, the capacity for evolution of the resulting platform cannot be totally ensured. In fact, if the simulator implementing the management and controlling tasks gets obsolete, its replacement in favour of a newer simulator would be challenging. In addition, TraNS, Veins and OVNIS require cooperative ITS application developers to integrate their applications into one of the combined simulators, which requires becoming familiar with this simulator. This may increase the time for development, and therefore reduce the usability of the platform.

iTETRIS goes one step beyond the limitations of the presented state of the art cooperative ITS simulators. iTETRIS proposes integrating two reference open source traffic and wireless communications simulators, namely SUMO and ns-3, through a novel interfacing middleware that is independent from their respective implementations (Figure 4-2d). In addition, it allows the language-agnostic implementation and testing of cooperative ITS applications. As a result, it offers better evolution perspectives, and facilitates the potential substitution of one of its interconnected simulation platforms. A key feature of iTETRIS with respect to other cooperative ITS simulators is its standard compliance with the ETSI ITSC architecture [28].

4.3 iTETRIS

iTETRIS is a unique ETSI ITSC standard compliant and open source simulation platform for cooperative ITS applications and protocols. It was developed under the EU FP7 Program "iTETRIS: an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions" [17]. iTETRIS' open source code is available for download at [97]. The iTETRIS architecture is shown in Figure 4-3. iTETRIS integrates and extends the open source traffic and wireless communications simulators SUMO and ns-3. It allows the implementation of cooperative ITS applications in various programming languages over a block called iAPP (iTETRIS implementation of a cooperative ITS APPlication). SUMO, ns-3 and iAPP are interconnected through a central controlling and interfacing middleware called iCS (iTETRIS Control System).

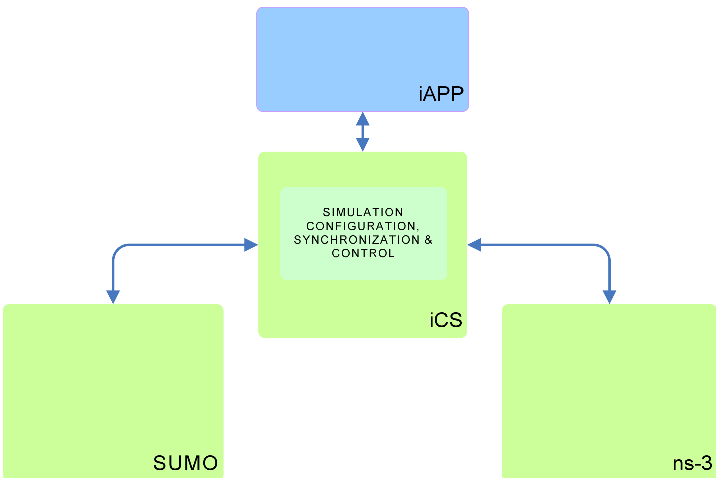


Figure 4-3. iTETRIS architecture.

The iTETRIS' modular architecture and open source nature facilitate future extensions. iTETRIS is also capable to simulate large scale scenarios, which represents a very appealing feature for investigating cooperative ITS systems and protocols. The author of this thesis contributed to the design and development of iTETRIS. As a result, the operation of the platform, and its different components are described in the following sections.

4.3.1 Wireless communications simulation

To simulate wireless communications, the iTETRIS consortium considered the possibility to adopt ns-2, ns-3 and OMNeT++ given that they are the three most used open source wireless simulators [135]. As selection criteria, the availability of communication modules and protocols, the platform stability, and the community support were taken into account. However, the most demanding requirement was the scalability capability under large scale simulation scenarios. In general, a detailed modelling of the lower layers of the wireless communications protocol stack can considerably increase simulation execution times and required memory resources [136]. In the particular case of cooperative ITS systems, the feasibility of large scale investigations may be further complicated when emulating the periodic exchange of standard CAM messages or network layer beacons among hundreds of vehicles. Studies such as [137] claim that OMNeT++ provides higher scalability compared to ns-2 and ns-3. However, this superior scalability was only due to a lower physical layer modelling accuracy compared to ns-2 and ns-3 [136]. After discarding OMNET++, the capability of ns-2 and ns-3 to support large scale simulations was analyzed. The results of this comparison are shown in [108]. The conducted study showed that ns-2 had strong RAM memory requirements, and was not able to handle simulations with more than 8000 nodes. On the other hand, ns-3 was capable to simulate scenarios with up to 20000 vehicles communicating with IEEE 802.11p radio interfaces. ns-3 was proven to enable such simulations even under extreme conditions in which up to 1000 nodes are in the interference range of each vehicle. The interference range was considered as the maximum inter-vehicle distance at which the simulator emulates the physical layer operations to sense packets. The authors of [108] also analyzed ns-3's scalability performance in terms of simulation execution time. For this analysis, they simulated under different configurations a 40s period in which 20000 vehicles communicate with each others. The results of this analysis are shown in Figure 4-4. The "Default" configuration corresponds to an unrealistic and worst case scenario in which the vehicular density is set to 727 vehicles/km^2. Vehicles broadcast beacons with a frequency of 10Hz, and the interference range is set to 700 meters. With these settings, the simulation execution time overpassed 100 hours. However, the authors identified mechanisms to simplify the ns-3 IEEE 802.11 PHY layer modelling. By modifying the interference management (“Mngt.” in Figure 4-4), or the interference calculation (“Interf.” in Figure 4-4), they obtained considerable simulation execution time reductions of up to nearly 30%. These modelling modifications did not imply a degradation of result’s accuracy. In the worst case, only a 1.8% difference in the number of correctly received packets was observed. Finally, the simulation was repeated using more relaxed and realistic conditions. The interference range was reduced to 100m (“100m” in Figure 4-4), and the beaconing frequency was set to 2Hz (“NL-2Hz” in Figure 4-4). Reducing the interference range emulates situations in which a vehicle detects fewer neighbours. This can represent more realistic traffic scenarios in which lower vehicular densities are experienced. In addition, transmitting beacons at lower frequencies emulates prospective situations in which algorithms for transmission rate control are adopted for lowering the communications load on the wireless channel. Both decreasing the interference range and the beaconing frequency reduce the number of packets that receiving vehicles have to process during the simulation. This resulted in lowering simulation execution times of up to 90%.

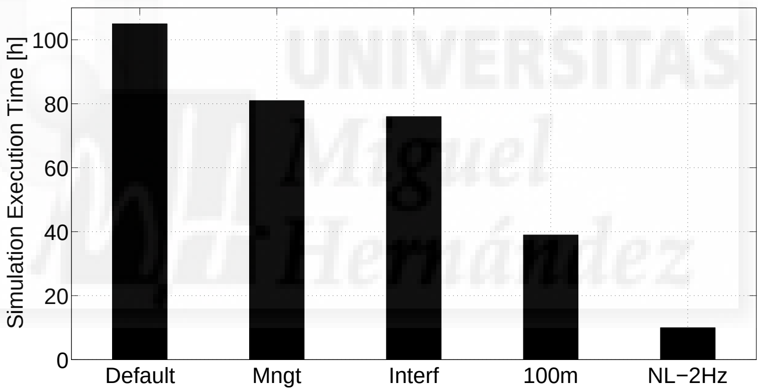


Figure 4-4. ns-3 large scale simulation execution times for varying simulation configurations [108].

The results obtained by [108] highlighted the scalability potential of ns-3, and justified its final adoption as wireless reference simulator for the iTETRIS platform. This investigation also demonstrated that a crucial trade-off exists between modelling accuracy and simulation execution time. This trade-off can be easily managed in iTETRIS thanks to its open source nature and considering the objectives of the simulation study. For example, the evaluation of cooperative safety applications over iTETRIS would require simulating a 10Hz CAM transmission frequency over small-sized scenarios. Such frequency could be reduced to just 1Hz in the case of larger-scale evaluations of traffic management applications without having a negative impact on the outcomes of the study. In both cases, the evaluations would be feasible with reasonable simulation execution times.

ns-3 is a discrete event-driven network simulator that provides its code under the GNU General Public License (GPL). Compared to its predecessor ns-2, ns-3 presents a more modular architecture, as well as multi-channel and multi-technology support. In addition, ns-3 is fully developed in C++ making use of programming solutions such as smart pointers, templates and object factories that highly ease the creation of new modules. Network entities are represented in ns-3 as "Nodes" (Figure 4-5).

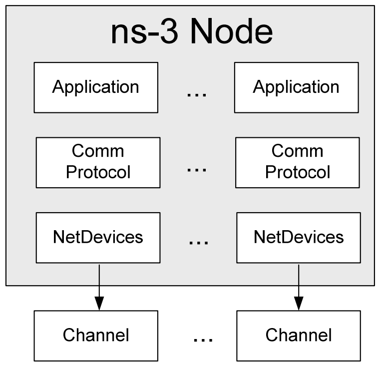


Figure 4-5. ns-3 Node layout.

Nodes can include multiple applications, communication protocols and technologies. Separate modules for each of these components can be incrementally aggregated to an ns-3 Node. In this context, ns-3 "Channels" model the effects generated by the (wired or wireless) medium adopted for communications between nodes. Channels are linked to modules called "NetDevices" modelling the Physical and Data Link layers of specific communication technologies installed on a node. The Network and Transport layers are modelled in ns-3 through the implementation of an IP communication stack (implementations for both IPv4 and IPv6 versions are available). Moreover, several modules implementing ns-3 "Applications" are available. These applications are used to generate communications traffic (e.g. "PacketSink", Ping, "UDPClient/Server", etc.). ns-3 provides specific "Helper" modules to create and configure nodes. Helpers can be used to install NetDevices, associate communication channels, and assign addresses at MAC and Network level. Helpers can also be used to easily create simulation scenarios. For this purpose, ns-3 uses simple C++ programs to be compiled, instead of OTcl scripts as in the case of ns-2.

4.3.2 Traffic simulation

For the choice of the reference open source traffic simulator, the iTETRIS consortium considered VanetMobiSim and SUMO. VanetMobiSim provides microscopic mobility modelling and support for representing real world road topologies. However, it was developed as a tool to retrieve vehicular mobility patterns to study cooperative vehicular communications. On the other hand, SUMO was developed as a tool for the evaluation of pure traffic engineering solutions at large scale. As a consequence, SUMO offers a more complete and accurate solution than VanetMobiSim. SUMO is also being used for research on VANETs. In fact, the vehicular mobility traces generated with SUMO can be easily exported to wireless communications simulators such as ns-2 and ns-3. For its higher precision and flexibility, SUMO was selected as iTETRIS' reference vehicular mobility simulator.

SUMO is a microscopic, space-continuous and time-discrete simulator. Like ns-3, its code is publicly available under the GNU GPL license. By only using standard C++ libraries, it provides high portability to different Windows and Linux platforms. SUMO is also highly interoperable with external supporting applications thanks to the adoption of XML data in many of its components. SUMO simulations are purely microscopic in the sense that each vehicle is modelled explicitly and individually, with a dedicated characterization in terms of mobility dynamics and route through the road network. SUMO supports the definition of different vehicle types characterized by distinct values of maximum speed, acceleration and length (among others). Interaction between vehicles is modelled based on the Krauß car-following model [138]. The road network is represented as a set of directed roads (called edges), lanes and road intersections. The latter can be modelled to emulate different transit rules (e.g. traffic lights or direction-based priority). The ability to manage road networks with more than 10000 edges with relatively fast simulation execution times makes SUMO suitable for large scale simulations [116].

Besides the traffic simulator itself, SUMO includes a number of additional tools and applications. For example, SUMO includes a GUI to visualize road traffic mobility. Other tools allow generating synthetic road networks and traffic flows. Specific SUMO applications permit importing real road network representations from different sources and formats, and converting them into SUMO representations. In addition, SUMO can enrich road network representations by adding additional infrastructure information such as bus stops or inductive loop sensors. An important feature of SUMO is that it allows external applications to connect to the simulator. This is possible through the use of an API called TraCI (Traffic Control Interface) that relies on a socket connection [139]. TraCI allows external applications to retrieve or modify values characterizing SUMO simulations (e.g. vehicles' speeds or positions, traffic lights' schedules, etc.).

In the context of the iTETRIS platform, TraCI was improved and extended by defining commands and variable identifiers that SUMO can easily interpret. With these improvements, the new TraCI can retrieve information about fuel consumption, noise and pollutant emissions, and dynamically change (e.g. upon reception of V2V or V2I messages) pre-established vehicles' routes in simulation runtime. Besides the improvement of TraCI, iTETRIS extended SUMO with appropriate solutions for the realistic assessment of cooperative ITS applications at large scale. In this context, new methods were implemented to model fuel consumption, noise and pollutant emissions of simulated vehicles. SUMO methodologies to import real world road networks and traffic demands representations from other formats were also improved. Some of the SUMO-compatible road network representations resulting from the application of these tools are depicted in Figure 4-6. The figure shows different areas of the Italian city of Bologna that were selected in the iTETRIS project to test the effectiveness of cooperative ITS traffic management applications in large scale scenarios. The selected areas include interurban (Figure 4-6a), city centre (Figure 4-6b), and urban neighborhood (Figure 4-6c) scenarios. More information about the SUMO extensions performed in the iTETRIS project can be found in [98].

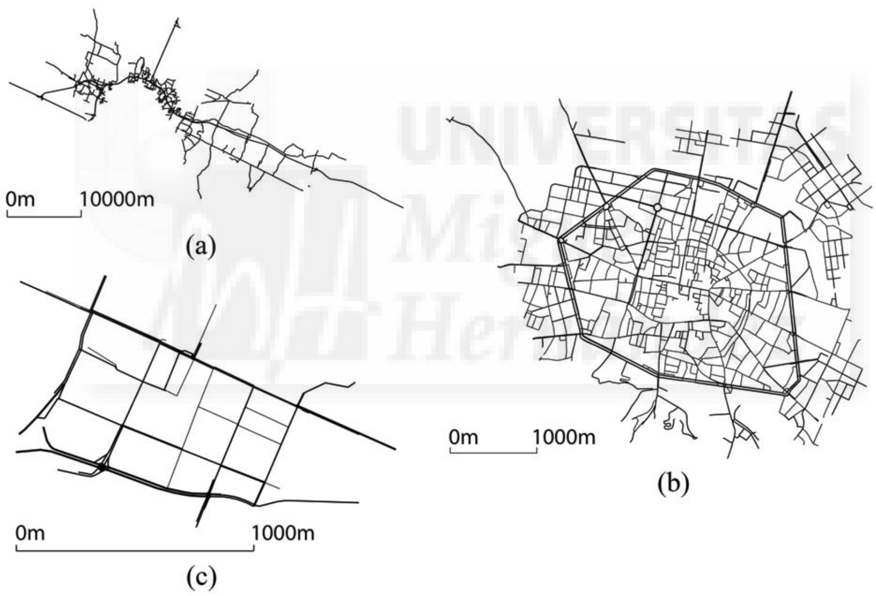


Figure 4-6. Bologna traffic scenarios imported to iTETRIS.

4.3.3 iTETRIS architecture

iTETRIS supports the simulation of cooperative ITS applications running on centralized Traffic Management Centers (TMCs), individual radio equipped vehicles or Roadside Units (RSUs). Applications running on these nodes are implemented in the iAPP block of iTETRIS. iTETRIS does not simulate backbone communications between the TMC and the communication infrastructure nodes. Therefore, a TMC does not require to be modelled either in SUMO or in ns-3. The iTETRIS representation of a TMC is only needed in the iAPP for the implementation of cooperative applications running on it. On the other hand, vehicles, RSUs, and other communication infrastructure nodes exchange wireless messages. Therefore, they need to be emulated in ns-3. In addition, vehicles are also represented in SUMO to simulate their mobility. To handle the representation of the same node over the distinct blocks of the platform, iTETRIS implements a new central block referred to as iCS (iTETRIS Control System). The iCS handles SUMO and ns-3 interaction, in addition to preparing, triggering, coordinating and controlling the execution of iTETRIS simulations. The resulting iTETRIS architecture is represented in Figure 4-7. The figure also maps the real world aspects modelled and simulated over the distinct blocks of the platform. SUMO simulates vehicles' mobility, pollutant and noise emissions, and fuel consumption. It also supports detailed representations of large scale traffic scenarios in terms of road networks, traffic demands, traffic lights management, and road intersection transit policies. ns-3 accurately simulates cooperative ITS communications in heterogeneous communication scenarios. It includes suitable models to reproduce radio propagation effects and emulate functionalities and protocols for every layer of the communication protocol stack. iTETRIS is aligned with the ETSI ITSC architecture described in Section 2.3 (white blocks in Figure 4-7). ns-3 implements models for all the communications-related layers of the ITSC architecture. An exception is made for the security layer that is not included in the initial iTETRIS release, but could be integrated at a later stage. The iCS provides some supporting functionalities for the cooperative ITS application implemented in the iAPP. Consequently, the implementation of the ITSC Facilities layer has been split between ns-3 and iCS. The Facilities more closely related to cooperative ITS applications and thereby requiring a higher interaction with the iAPP (e.g. the Local Dynamic Map introduced in Section 2.3) are implemented on the iCS ("iCS Facilities" in Figure 4-7). On the other hand, the Facilities needed to support wireless communications (e.g. the CAM and DENM services described in Section 2.6) are implemented in ns-3 ("ns-3 Facilities" in Figure 4-7). Thanks to implementation approach, the iCS and ns-3 do not have to call from an external block the Facilities needed for their internal operations. This significantly reduces the exchange of messages between ns-3 and the iCS, and consequently also the required computational resources and simulation execution time.

All the iTETRIS blocks interact through the iCS using a set of open interfaces. The adopted interfacing scheme is based on IP sockets. In this context, the iCS can communicate with the other blocks by just specifying on which IP address and port the SUMO, ns-3 and iAPP blocks have to listen to. A client/server association between the iCS and the other blocks is adopted, with the iCS always acting as client. The iCS presents three internal components: the Traffic Simulator Communicator, the Wireless Simulator Communicator, and the Application Manager (Figure 4-7). Through dedicated client entities implemented in these components, the iCS triggers actions to be simulated in the other blocks (e.g. wireless transmissions or vehicle movements), and actively requests the resulting outcomes (e.g. wireless message receptions or vehicle position updates). Server entities implemented in the other iTETRIS blocks reactively accomplish the tasks requested by the iCS.

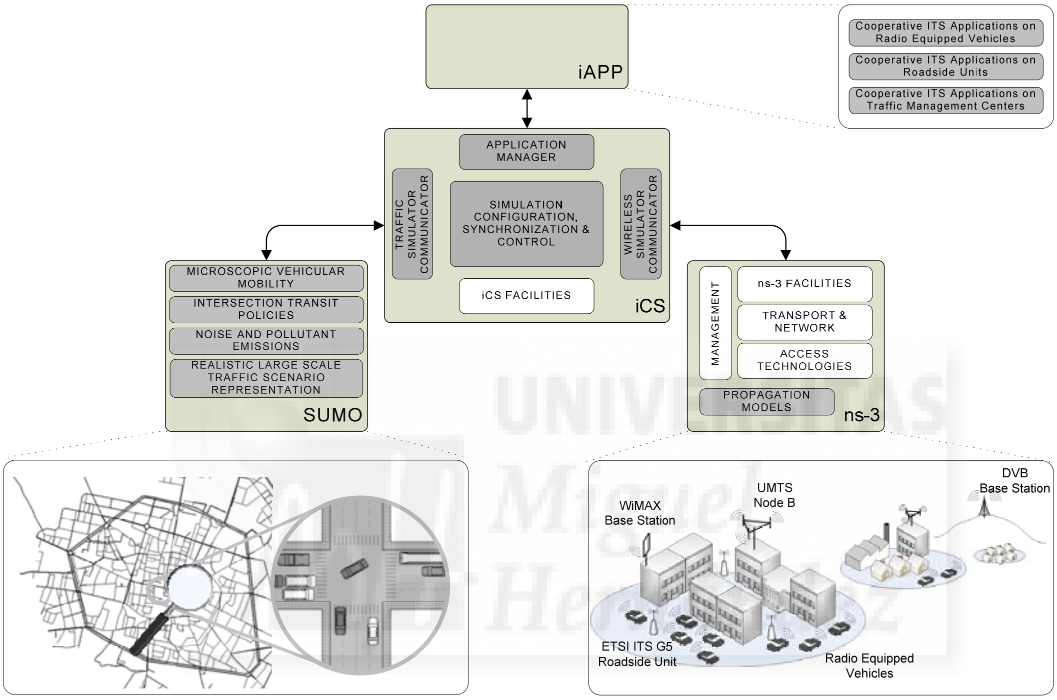


Figure 4-7. Detailed iTETRIS architecture.

4.3.4 Simulation process

The execution of iTETRIS simulations is controlled by the iCS. First, the iCS sets up the simulation environment by initialising all the iTETRIS configurable objects. To improve the readability of simulation configurations, a hierarchical XML configuration file structure is adopted (Figure 4-8a). In this context, the master configuration file defines general parameters such as the duration (in seconds) of the time period to simulate, the penetration rate of radio access technologies on simulated vehicles, and the sockets' IP addresses and port numbers needed by the iCS to communicate with ns-3, SUMO and the iAPP. The master configuration file also includes the path to the files used to configure ns-3, SUMO and the iAPP. When iTETRIS is started, SUMO and ns-3 are launched by the iCS. Their executables are registered in separate threads so that, from that point on, they can receive commands. By reading the iAPP configuration file, the iCS allocates a dedicated execution thread for a simulated cooperative ITS application. The Facilities configuration file is read to create the iCS Facilities. The SUMO and ns-3 configuration files are analyzed to prepare the traffic and wireless simulation environments. Road map, vehicular traffic flows, and communication parameters of the simulated wireless technologies are set up in this phase. More detailed instructions on how to write iTETRIS configuration files, and simulate cooperative ITS applications in iTETRIS can be retrieved from the iTETRIS community webpage [97].

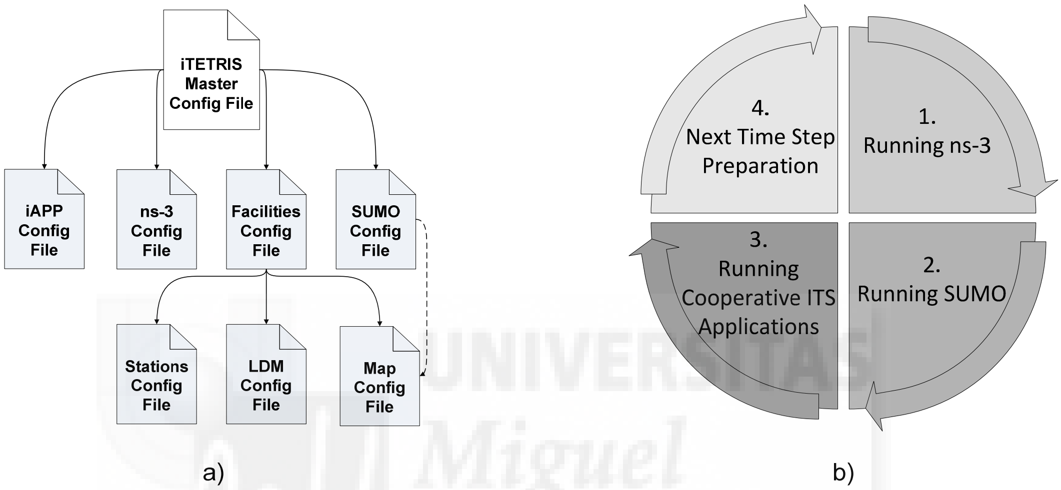


Figure 4-8. iTETRIS' configuration files hierarchy (a) and run-time loop iteration (b).

In iTETRIS, the simulated time period is divided into simulation time steps of one second. For each simulated time step, iTETRIS executes a run-time loop (Figure 4-8b) in which ns-3, SUMO and the iAPP are sequentially triggered by the iCS to execute their tasks. ns-3, SUMO and the iAPP respectively simulate all the wireless communication, traffic, and ITS application events scheduled for the corresponding time step. The entry point in the run-time loop is the simulation of wireless transmissions in ns-3. The application's payload of transmitted messages is created and stored in the iCS. When the iCS schedules message transmissions in ns-3, a reference to these payloads is passed to ns-3. Once ns-3 has simulated all the transmissions scheduled for the current time step, the iCS uses the Wireless Simulator Communicator to retrieve the results of these simulations. ns-3 simulation results are coded as a list of messages that have been correctly received by recipient nodes. By matching the received messages with the previously stored payloads, the iCS can update specific iCS Facilities (i.e. the LDM database) that can be accessed by the application implemented in the iAPP.

In the following stage of the run-time loop, SUMO is triggered to simulate all the traffic mobility events of the established time step. After these simulations, the iCS' Traffic Simulator Communicator retrieves from SUMO new position and speed of already active vehicles, along with position and speed of vehicles entering the simulated scenario in the current time step. To each of these new vehicles, the iCS assigns a radio access technology following the penetration rate values reported in the master configuration file. If a vehicle is assigned a radio access technology, it can then execute cooperative ITS applications. As a result, a structure for this vehicle is created in the iCS in order to link its SUMO and ns-3 representations. The retrieved vehicle speeds and positions are used by the iCS to update other iCS Facilities. These facilities store vehicular mobility information that could be used by the application implemented in the iAPP.

After that, The iCS triggers the simulations of cooperative ITS applications for the current time step. iTETRIS can support simulation of simultaneous and possibly interactive cooperative applications. Therefore, more than one iAPP blocks can be present. The iCS' Application Manager asks every iAPP to "subscribe" to the SUMO and ns-3 simulation results needed to execute their application. Based on these subscriptions, the iCS forwards the solicited information to iAPPs. After executing the applications implemented in the iAPPs, the iCS retrieves the iAPPs' results that in turn may generate new actions to be executed over SUMO or ns-3 (e.g. transmission of new messages, rerouting of vehicles, etc.).

The last stage of the run-time loop is devoted to prepare the simulation of the next time step in ns-3. The iCS' Wireless Simulator Communicator schedules the simulation of new transmissions. Moreover, based on SUMO outcomes, it commands ns-3 to create new radio-equipped vehicles, and update the position of vehicles that are already being simulated.

At the end of a run-time loop, the iCS updates the time step counter, and checks whether its value equals the duration of the time period to simulate. If this is the case, the simulation is concluded. Otherwise, a new run-time loop is performed. At the end of a simulation, the iCS cleans up the objects allocated in the memory, closes logging files (if they were defined), shuts down the connections with ns-3, SUMO and the iAPPs, and eliminates the threads in which they were executed.

4.3.5 iTETRIS innovations

iTETRIS makes important advances in the field of cooperative ITS simulation. According to the knowledge of this thesis' author, none of the existing cooperative ITS simulation platforms jointly provide iTETRIS' capability to:

- Allow language-agnostic implementation and simulation of cooperative ITS applications thanks to open interfaces that abstract application developers from the intrinsic technological aspects of both traffic and wireless simulators;
- Extend its open source wireless and traffic simulators separately and independently from the internal implementation of the rest of the iTETRIS blocks;
- Provide implementation modules that are fully compliant with the ETSI standards for Intelligent Transport Systems Communications (ITSC). Consequently, iTETRIS allows testing and optimizing novel cooperative ITS applications and protocols using standard compliant systems prior to a prototype implementation and field tests;
- Support realistic large scale simulations while accurately modelling standard-compliant cooperative ITS systems;
- Modify the modelling accuracy based on the study objectives and constraints. This is particularly relevant in the case of modelling the wireless physical layer since it has a significant impact on the simulation execution time.

Table 4-3 compares iTETRIS' features with those of the existing cooperative ITS simulation platforms described in Section 4.2.3. The table compares important aspects such as the modelling accuracy, the platform modularity and capability to be extended, the support for external applications, the implementation of standard-compliant cooperative ITS communication protocols and technologies, and the capability to simulate large scale scenarios. Although all the other existing cooperative ITS simulation platforms provide high modularity in protocol implementations, Table 4.3 confirms that iTETRIS exhibits a higher modularity in the way its communications, mobility and application blocks are separated and can be recombined. This results in a high capability for evolution, as it allows for an independent development, or even replacement, of its interconnected simulators. iTETRIS' open interfacing approach permits the language agnostic-implementation of cooperative ITS applications. In addition, iTETRIS is one of the few platforms allowing large scale evaluations of cooperative ITS applications over a complete set of cooperative ITS standard-compliant communication protocol implementations. To the author's knowledge, iTETRIS is currently the only platform implementing the ETSI ITSC architecture.

Simulation Platform	Communications modelling accuracy	Mobility modelling accuracy	Modularity in communications, mobility, and applications simulation blocks	Open source availability	Capability for evolution	Capability to support external applications coded in different languages	Compliance with standard cooperative communication stacks	Support for large scale simulations
MOVES [123]	Medium	Medium	Low	Not proved	Low	No	No	Yes
AutoMesh [124]	High	Medium	Medium	Not proved	Low	Not proved	No	Yes
VANET [125]	Medium	Medium	Low	Not proved	Low	No	No	Yes
GrooveSim [126]	Medium	Medium	Medium	Yes	Low	No	IEEE 802.11p/1609	Yes
SWANS Extensions [127][128]	High	Medium	Low	Yes	Low	No	No	Not proved
ns-3 Extensions [129]	Very high	Medium	Low	Yes	Low	No	No	Not proved
NCTUns [111]	Very high	Medium	Low	Yes	Low	Yes	IEEE 802.11p/1609	Yes
CORSIM/ Qualnet [130]	High	High	Medium	No	Low	No	No	Not proved
VISSIM/ns-2 [131]	Very high	High	Medium	No	Low	No	No	Yes
TraNS [132]	Very high	High	Medium	Yes	Low	No	No	Not proved
Veins [133]	Very high	High	Medium	Yes	Low	No	IEEE 802.11p/1609	Yes
OVNIS [134]	Very high	High	Medium	Yes	Low	No	No	Yes
iTETRIS	Very high	High	High	Yes	High	Yes	ETSI ITSC	Yes

Table 4-3. Comparison of iTETRIS with existing cooperative ITS simulation platforms.

4.4 ns-3 testbed

The entire iTETRIS platform, as the set of all its constituting blocks, has been used in this thesis for the implementation and evaluation of the dissemination protocol proposed in Chapter 7. This protocol is supported by a centralized information processing scheme running at the TMC. This processing scheme can be seen as part of a cooperative application, and hence its implementation has been realized over the iTETRIS' iAPP block (Figure 4-7). The protocols proposed in Chapter 5 and 6 are fully distributed and are not controlled by any centralized application. On the nodes running these protocols, no Applications layer operation needs to be performed. Protocol messages are generated and received at the Transport & Network layer of the ETSI ITSC architecture, and processed over the underlying layers of the protocol stack. All these layers are modelled in the ns-3 block of iTETRIS. As a result, the communication protocols described in Chapters 5 and 6 do not need to be evaluated over the entire iTETRIS platform, but can be tested on a testbed formed by the ns-3 block of iTETRIS. The ns-3 block of iTETRIS is an evolved implementation of the ns-3 simulator realized in the iTETRIS project. The author of this thesis actively contributed to implement this evolved version of the ns-3 wireless simulator. For this reason, this section provides a more detailed overview of this implementation.

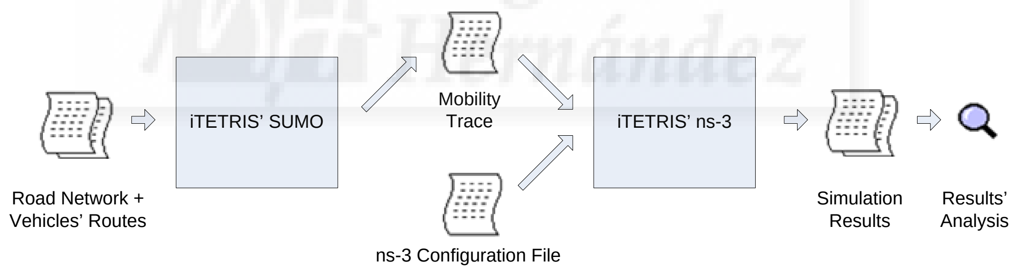


Figure 4-9. Simulation process with the ns-3 testbed.

For evaluations using this ns-3 testbed , the process illustrated in Figure 4-9 has been followed. Vehicular mobility traces are generated by SUMO and reused in the iTETRIS implementation of ns-3. A traffic scenario composed by road network and vehicles' routes is built. With these inputs, SUMO simulates vehicle movements and generates traces specifying vehicle positions and absolute speeds with a time resolution of one second. These mobility traces are then converted into a compatible format and provided to ns-3 as a wireless simulation input. Wireless simulation configuration parameters (such as the adopted radio technologies and propagation models, transmission powers, antenna heights, etc.) are fed to ns-3 in the form of an XML configuration file. ns-3 prepares the simulation by reading the configuration file and the mobility trace. This is accomplished by specific classes implemented in the iTETRIS project. The simulation results generated by ns-3 are logged in specific text files and analyzed by software tools like Matlab.

A graphical description of the extensions and modifications performed in the iTETRIS project over the official distribution of ns-3 is depicted in Figure 4-10. The rest of this section gives a detailed description of this implementation. These modifications and extensions enable realistic and standard-compliant simulations of vehicular communication protocols, and hence are crucial for the evaluation and validation of the communication schemes proposed in this thesis.

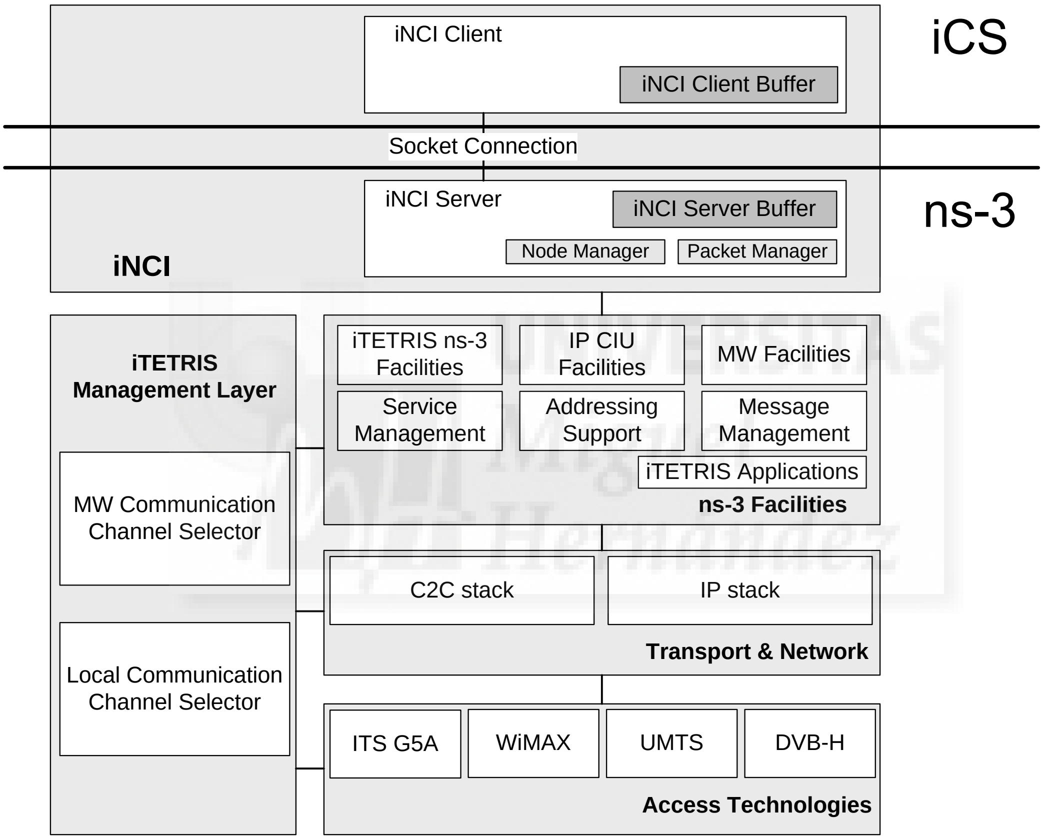


Figure 4-10. iTETRIS' ns-3 implementation and interfacing system to the iCS.

4.4.1 iNCI interface

Differently from SUMO, the default version of ns-3 does not provide interfaces for the interaction with external modules. In iTETRIS, such interaction is necessary to let ns-3 receive vehicle position updates from SUMO. In addition, the iAPP block must be able to trigger simulations of ns-3 transmissions, and receive ns-3 notifications about the outcomes of these simulations. In iTETRIS, ns-3 interacts with the SUMO and iAPP blocks through the iCS. To allow a bidirectional exchange of information between ns-3 and the iCS, the iTETRIS Network simulator Control Interface (iNCI) is implemented. This interaction is carried out by means of primitives between an iCS client (iNCI Client) and an ns-3 server (iNCI Server) communicating through IP sockets (see Figure 4-10). The iNCI Server consists of two main entities: the Node Manager and the Packet Manager.

4.4.1.1 iNCI Node Manager

The Node Manager implements specific primitives used by the iCS to dynamically create new ns-3 nodes, and update their position and speed at each simulation time step. As defined in Section 4.3.1, the modularity of ns-3 permits aggregating several modules to a node. Following this approach, iTETRIS defines Communication Modules as sets of ns-3 classes modelling components of the various ITSC layers, and that can be separately installed on a node. For example, the ITS G5A communication module includes all the ns-3 classes used by the simulator to model the operation of the ETSI ITS G5A access technology. Similarly, communication modules for the components of the ITSC Transport & Network layer are defined, and so on. To install specific communication modules, dedicated Communication Module Installers are defined. When a primitive to create a new ns-3 node is called, these installers install communication modules according to the node's type as specified by the user in the ns-3 configuration file. Distinct primitives are defined to create different types of ns-3 nodes: vehicles, Communication Infrastructure Units (CIUs) and Middleware (MW) nodes. CIUs refer to ITS G5 RSUs and other communication infrastructure nodes such as UMTS, WiMAX or DVB base stations. A MW node is an entity defined by iTETRIS. It assists the TMC in the centralized selection of the most appropriate CIU to disseminate traffic information over a geographical target area. A MW node is virtually tied to both TMC and CIUs through backbone connections. Since iTETRIS focuses on wireless communications between vehicles, and between vehicles and infrastructure nodes, communications over such backbone network are not modelled.

4.4.1.2 iNCI Packet Manager

The Packet Manager implements the primitives that the iCS uses to trigger ns-3 simulation of message transmissions, and to retrieve information about correctly received messages. Some of these primitives are listed in Table 4-4. The primitives are labelled following the type of transmission mode used to perform a given cooperative service. Examples of cooperative ITS services are the CAM and DENM services defined in Section 2.6. Specific primitives are defined for these services. Each primitive identifies specific nodes that have to activate or deactivate the transmission of service messages in ns-3. For example, ACTIVATE_CAM_TXON and DEACTIVATE_CAM_TXON are used to start and stop the periodic transmission of CAM messages. Each of the primitives in Table 4-4 is defined through a different set of parameters, whose meaning is described in Table 4-5.

Primitive	Description	Parameters
ACTIVATE_CAM_TXON	Requests ns-3 to activate the transmission of CAM messages on a given node (Vehicle or RSU).	NodeId, PayloadLength, TransmissionFrequency
DEACTIVATE_CAM_TXON	Requests ns-3 to deactivate the transmission of CAM messages on a given node (Vehicle or RSU).	NodeId
ACTIVATE_DENM_TXON	Requests ns-3 to activate the transmission of DENM messages on a given node (Vehicle or RSU) and on a geographic destination area.	NodeId, PayloadLength, Destination, TransmissionFrequency, MsgRegenerationTime
DEACTIVATE_DENM_TXON	Requests ns-3 to deactivate the transmission of DENM messages on a given node (Vehicle or RSU).	NodeId
ACTIVATE_TOPO_TXON	Requests ns-3 to activate the TopoBroadcast transmission of a message on a given node (Vehicle or RSU).	NodeId, ServiceId, TransmissionFrequency, Destination, PayloadLength, MsgRegenerationTime, MsgLifetime, NumHops
ACTIVATE_GEO_BROAD_TXON	Requests ns-3 to activate the GeoBroadcast transmission of a message on a given node (Vehicle or RSU).	NodeId, ServiceId, TransmissionFrequency, Destination, PayloadLength, MsgRegenerationTime, MsgLifetime
ACTIVATE_ID_BASED_TXON	Requests ns-3 to activate (on a vehicle or RSU) the transmission of a message based on the ID of the destination. This primitive can be used to activate either unicast or broadcast transmissions (in the latter case, the destination ID is a broadcast constant). If the sender is a vehicle and the destination is the TMC, the transmission can be executed over one of the different radio access technologies and communication stack the vehicle is equipped with according to a given communication profile suggested by the iAPP.	NodeId, ServiceId, CommProfile, ListOfTechnologies TransmissionFrequency, PayloadLength, Destination, MsgRegenerationTime, MsgLifetime
ACTIVATE_IPCIU_TXON	Requests ns-3 to activate (on a CIU) the transmission of a message based on the ID of the destination. This primitive can be used to activate IP unicast, broadcast or multicast transmissions (in case of broadcast or multicast transmissions, the destination ID is a broadcast/multicast constant).	NodeId, ServiceId, TransmissionFrequency, PayloadLength, Destination, MsgRegenerationTime
ACTIVATE_MW_TXON	Requests ns-3 to activate the transmission of a notification message to a geographical area using the MW node. The selection of the most appropriate CIU to transmit the message is requested by the MW node to the Management Layer according to a given communication profile suggested by the iAPP.	NodeId, ServiceId, CommProfle, ListOfTechnologies, TransmissionFrequency, PayloadLength, Destination, MsgRegenerationTime, MsgLifetime
GET_RECEIVED_PACKETS	Requests ns-3 to return the messages received by a given node.	NodeId

Table 4-4. iNCI Packet Manager primitives.

The values of the parameters indicated in Table 4-5 can be specified by the cooperative ITS applications implemented in the iAPP. When the ns-3 simulation of message transmissions is triggered by an application, the iCS introduces these values into the corresponding primitives. When a primitive is called, the Packet Manager identifies the ns-3 nodes that are requested to transmit. To activate transmissions, it calls specific functions implemented in the Facilities layer of these nodes. After simulating the transmission of messages, ns-3 indicates to the iCS which nodes correctly received these messages. For this purpose, the iCS calls the CMD_GET_RECEIVED_PACKETS primitive.

Parameter	Description
ServiceID	Identifier of the cooperative ITS service
NodeId	Identifier of the node over which the cooperative ITS service has to be activated or deactivated
PayloadLength	Payload size of the service message to be activated
TransmissionFrequency	Transmission frequency of the service message to be activated
MsgRegenerationTime	Time period over which the service message to be activated has to be periodically transmitted
MsgLifetime	Time during which the service message to be activated has to be considered valid by recipient nodes
Destination	Destination of the service message to be activated. It can be a geographical circular destination area where a message has to be disseminated (for ACTIVATE_GEO_BROAD_TXON, ACTIVATE_MW_TXON primitives), or the identifier of a specific destination node (for ACTIVATE_ID_BASED_TXON, ACTIVATE_IPCIU_TXON primitives)
NumHops	Maximum allowed number of hops the service message is allowed to be forwarded
ListOfTechnologies	Set of suitable radio access technologies (ITS G5, UMTS, etc) that can be used to execute a cooperative ITS service
CommProfile	Communication profile suggested by the iAPP for the cooperative ITS service

Table 4-5. Parameters of the iNCI Packet Manager primitives.

4.4.2 ns-3 Facilities

The Facilities layer of every ns-3 node generates the messages to be transmitted, and implements the necessary functions required to correctly forward these messages to the lower layers of the communication protocol stack. The ns-3 Facilities are also responsible to forward received messages to the iNCI Packet Manager, so that the iCS can be informed about these receptions. To generate and receive service messages at Facilities level, iTETRIS defines ns-3 classes called iTETRISApplications. iTETRISApplications are conceptually similar to other ns-3 applications (e.g. Ping or UDPClient/Server) used to generate communications traffic (e.g. “Ping” or “UDPClient/Server”). When a node is created in ns-3, specific iTETRISApplications (each of them supporting a specific service) are installed on it. These iTETRISApplications are installed according to the instructions specified in the ns-3 configuration file (e.g. vehicles and RSUs have iTETRISApplications for CAM and DENM services installed by default). On every node, these services are stored in a list of services called ServiceList, and are associated to a

ServiceId. Using these identifiers, the iCS can call and execute, when required, the correct iTETRISApplication to start the transmission of specific service messages

Besides the iTETRISApplication classes, the implementation of the ns-3 Facilities layer on a given ns-3 node requires distinct additional classes depending on the type of node. Vehicles and RSUs use the iTETRISns3Facilities class, the rest of CIUs (UMTS, WiMAX and DVB base stations) the IPCIUFacilities class, and MW nodes the MWFacilities class (Figure 4-10). When the iNCI PacketManager has to activate one of the iTETRISApplications installed on a node, it calls specific functions provided by the above mentioned ns-3 Facilities classes. For example, the iTETRISns3Facilities class includes functions to activate or deactivate the periodic transmission of CAM messages, or to activate generic transmissions over the C2C or IP stacks. When calling these functions, many of the parameters indicated in the Packet Manager primitives (Table 4-5) are reused. As indicated in Table 4-5, the iAPP can specify the candidate radio access technologies (ListOfTechnologies) to execute a given service. It can also indicate its communication requirements by suggesting a communication profile (CommProfile) parameter. If the ListOfTechnologies parameter defines more than one candidate radio access technology, then one of them has to be selected to execute the service. In the current iTETRIS release, this situation can only occur in two cases. It can occur in the iTETRISns3Facilities class whenever a vehicle equipped with multiple radio access technologies wants to communicate with the TMC (in response to the primitive ACTIVATE_ID_BASED_TXON defined in Table 4-4). Otherwise, it can occur in the MWFacilities class when the TMC wants to disseminate a traffic message over a target area and can use different types of communication infrastructure nodes to do so (ACTIVATE_MW_TXON primitive in Table 4-4). In both cases, the selection is performed by calling functions provided by the iTETRIS ns-3 Management layer that are described in the next section.

The iTETRISns3Facilities, IPCIUFacilities and MWFacilities use additional ns-3 Facilities classes. In particular, the AddressingSupport, ServiceManagement and MessageManagement classes are defined. Figure 4-11 illustrates some of the functions provided by these classes and how they are sequentially called when the transmission of a service message is activated at Facilities level. As it can be seen, once all the communication parameters have been set on the iTETRISApplication identified by ServiceID, the MessageManagement class can finally activate message transmissions. From this point on, the identified iTETRISApplication starts to autonomously generate service messages as requested by the cooperative ITS application implemented in the iAPP.

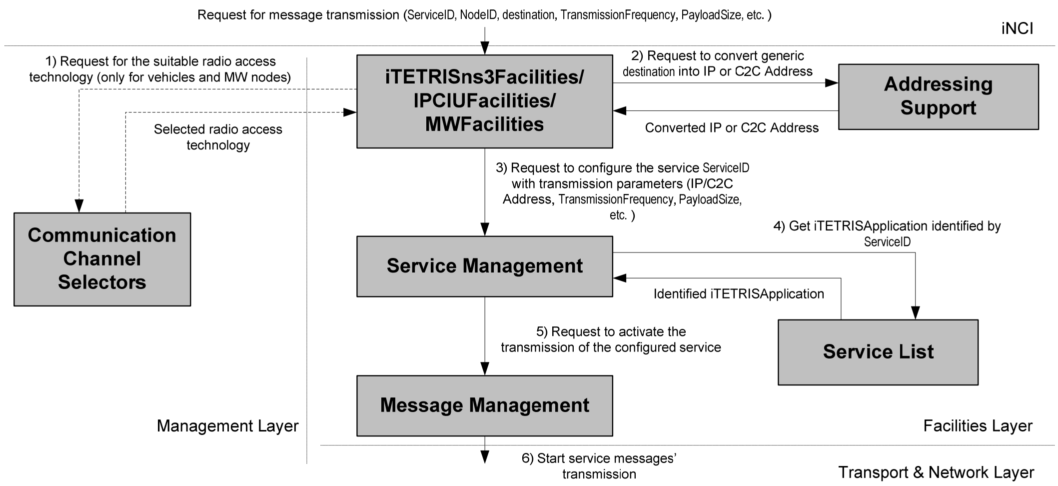


Figure 4-11. iTETRIS' ns-3 Facilities architecture.

4.4.3 Management layer

As anticipated in the previous section, the iTETRIS ns-3 Management layer focuses on communication management issues. In particular, it is in charge of selecting the most suitable radio access technology and communication protocol (referred to as Communication Channel or Communication Profile by ETSI [140]) to operate a given service. This selection should be taken dynamically based on the application requirements and the current status of the available radio access technologies. In iTETRIS, the selection can be "local" or "global". A local communication channel selection is adopted by vehicles equipped with multiple radio access technologies. On the other hand, a global communication channel selection is needed by the TMC to select the most suitable CIU to disseminate traffic messages over a target area. For this purpose, iTETRIS uses the previously defined MW node.

The current iTETRIS release partially simplifies the communication channel selection process to facilitate the execution of large scale simulations. The iTETRISns3Facilities class calls the LocalCommChSelector class implemented in the Management layer to realize the local communication channel selection on vehicles (Figure 4-10). For this purpose, the list of suitable radio access technologies (ListOfTechnologies) and the suggested communication profile (CommProfile) are passed to the LocalCommChSelector. Based on the suggested CommProfile, the service to be activated is mapped by the LocalCommChSelector into a set of generic profiles that represent different possible cooperative ITS applications' requirements. Each of these profiles is then associated to one or more suitable radio access technologies according to the rules defined in the communication channel selector. For example, in the current iTETRIS version the 'High

Priority' profile is only associated to ITS G5, while the 'Traffic Efficiency' profile can be associated to any access technology. Once the list of suitable radio access technologies has been established for the identified profile, the selector compares this list with the ListOfTechnologies parameter received from the Facilities layer. It then checks whether one of the suggested radio access technologies is present and active on the vehicle. To do so, the VehicleStaMgnt class, installed on every simulated vehicle, is used. This class returns the RSUs and CIUs currently offering radio coverage to the vehicle. The first suitable radio access technology in the list is selected to activate service transmissions.

A similar approach is used for the global communication channel selection on MW nodes. In this case, the MWFacilities class calls the MWCommChSelector class. This call specifies the CommProfile and ListOfTechnologies parameters, along with the geographical coordinates of the target area where the TMC wants to disseminate its service messages (Destination). By combining this information with the knowledge of the position of deployed CIUs and the number of vehicles they serve (this information can be retrieved from specific CIUMngt classes), the selector can decide which is the most suitable CIU to disseminate a given message. In the current iTETRIS release, the first access technology in the ListOfTechnologies that offers coverage to a satisfactory number of vehicles is selected to transmit messages.

4.4.4 Transport & Network layer

iTETRIS enriches the official ns-3 release by implementing the C2C communication stack based on the definitions of the ETSI ITSC GeoNetworking stack [31]. As explained in Section 2.3, the ITSC GeoNetworking stack offers the transport and networking capabilities needed in vehicular ad-hoc communication environments. In this context, the GeoNetworking communication paradigm is reproduced in iTETRIS through the implementation of the four basic GeoNetworking transmission modes GeoUnicast, GeoBroadcast, TopoBroadcast and GeoAnycast defined in Section 2.5.1. These basic GeoNetworking transmission modes are implemented in the ns-3 version of iTETRIS by following the specifications of the ETSI standard [33] and the European project GeoNet [34].

The C2C stack developed in ns-3 by iTETRIS (Figure 4-12) is similar in structure and operation to the existing ns-3 IPv4 and IPv6 stacks, except for the use of specific addresses (called C2CAddresses), and the existence of dedicated interfaces to the Access Technologies Layer (C2CInterfaces). C2CSockets classes implement an asynchronous socket API system enabling the iTETRISApplications implemented in the Facilities layer to bind and listen to specific port numbers for the transmission and reception of messages. The C2CTransportProtocol class' implementation follows the lightness requirements imposed by vehicular environments to transport layer functionalities [32]. The C2CL3Protocol class is responsible for the routing of transmitted and received messages according to the established GeoNetworking transmission mode. For its operation, it exploits the functionalities offered by the GeoRoutingProtocol class, which defines the core algorithms of the basic GeoNetworking transmission modes. In addition, the Beaconing Protocol and Location Table functionalities are implemented respecting the specifications of the standard [33]. As already introduced in Section 2.5.2, the Beaconing Protocol is used by all vehicles and RSUs to periodically broadcast beacon messages notifying their position and speed to neighbouring nodes. The Location Table is a dynamic database where vehicles and RSUs store and update geographical information received from neighbouring nodes. Such information is consulted to drive GeoNetworking decisions.

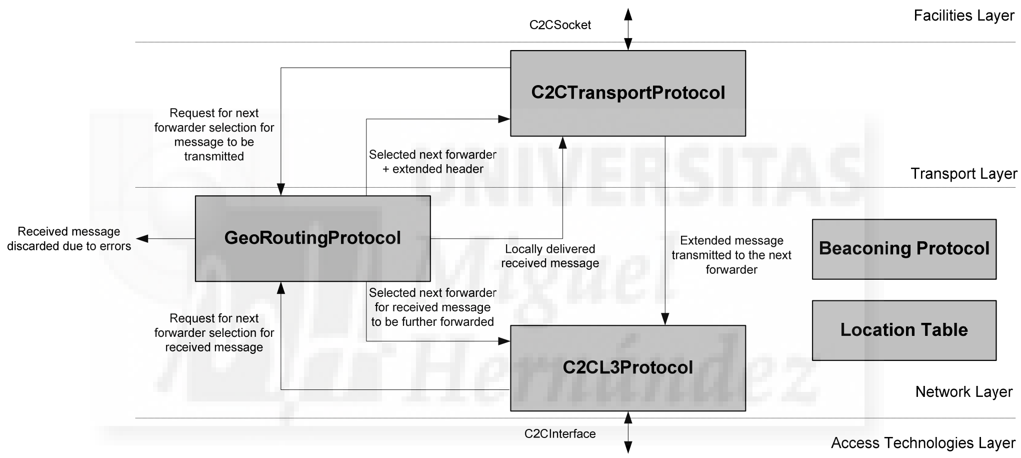


Figure 4-12. C2C stack architecture in the ns-3 version of iTETRIS.

In the iTETRIS ns-3 implementation, when a message to be transmitted is generated by an iTETRISApplication on a given node, it is sent to the C2CTransportProtocol through the C2CSocket. As shown in Figure 4-12, the C2CTransportProtocol requests the GeoRoutingProtocol to select the next forwarder of the message. GeoRoutingProtocol identifies the next forwarder by analyzing the C2CAddress of the final destination, which varies according to the requested GeoNetworking transmission mode. The C2CAddress specifies a circular destination area for GeoBroadcast and GeoAnycast transmission modes, a number of hops for the TopoBroadcast transmission mode, and a GeoUnicast address (represented as a combination of the ID and geographical position of the destination node) for the GeoUnicast transmission mode [33]. While identifying the next forwarder, the GeoRoutingProtocol class also extends the transmitted packet by adding a transmission mode-specific extended header containing the information specified by the destination C2CAddress. This information is used to drive the message forwarding at subsequent hops. The extended headers implemented by iTETRIS are the same as specified in Section 2.5.2 following the specifications of the ETSI ITS standard [33]. Once the next forwarder has been identified, the extended packet are passed down to the C2CL3Protocol class, which in turn adds the standard common header (see Section 2.5.2) specifying the GeoNetworking characteristics of the current sender node [33]. Finally, the C2CL3Protocol delivers the packet to the lower layers over a C2CInterface connecting the C2C stack to the attached Access Technologies.

An analogous standard compliant process is implemented for message receptions. When the C2CL3Protocol receives a packet from the lower layers, it calls the GeoRoutingProtocol class. GeoRoutingProtocol analyzes the information included in the packet's common header to understand to which transmission mode the message belongs. Once this information is retrieved, a transmission mode-specific protocol is called. The protocol decides whether to locally deliver the message to the upper layers (if the receiving node is the message's destination node), forward it (if the receiving node is not the message's destination node), or discard it (in case of errors). For this purpose, the called protocol analyzes the information contained in the received message's extended header. In case the received message has to be forwarded, the GeoRoutingProtocol class computes the next forwarder and returns the message to the C2CL3Protocol for further transmission.

Although iTETRIS only implements the four basic GeoNetworking transmission modes defined in [33] and [34], future deployments could require the coexistence of these transmission modes with other GeoNetworking protocols. To account for this possibility, the iTETRIS' C2C stack proposes an implementation supporting a list of routing protocols over the C2CListRouting class. Each of these routing protocols can be installed on ns-3 nodes, and be assigned a given priority. When needed during a simulation, these coexistent routing protocols are sequentially called to identify the next forwarder of a message. The final routing decision is taken according to the protocols' priority. In iTETRIS, the protocols of the four basic GeoNetworking transmission modes are specified and implemented by the GeoRoutingProtocol class. This class is installed by default on vehicles and RSUs with the lowest priority. By modifying the ns-3 configuration file, advanced GeoNetworking protocols with higher priorities can be added and used.

4.4.5 ETSI ITS G5A implementation

As shown in Figure 4-10, iTETRIS implements in ns-3 four different radio access technologies to offer a heterogeneous set of communication and networking solutions to support cooperative ITS applications. These radio access technologies are the vehicular ETSI ITS G5 standard in its operation mode 'A' (ETSI ITS G5A) [12], the cellular UMTS technology [141], the WiMAX (or IEEE 802.16 [142]) technology, and the DVB-H broadcasting system [143]. The ETSI ITS G5A is expected to be the dominant communication technology for the provision of cooperative ITS applications. Moreover, it is the main radio technology used by the communication protocols described in this thesis. For these reasons, this section describes its modelling and implementation over the iTETRIS version of ns-3.

4.4.5.1 Overview

Although the ETSI ITS G5 standard [12] distinguishes different operation modes for different classes of cooperative applications and frequency bands, iTETRIS only considers the ITS G5A mode employed for road safety and traffic efficiency applications. iTETRIS realized a new implementation of the ITS G5A radio access technology by modifying and extending the WiFi models of the ns-3.7 stable release [144] with a set of new functions and modules. As described in Section 2.4, ITS G5A relies on the IEEE 802.11p amendment [10], which in turn is an evolution of the IEEE 802.11a standard working with channels of 10MHz. Moreover, ITS G5 includes the IEEE 802.11e EDCA queuing mechanism for differentiation among packets belonging to applications having different QoS requirements. In this context, the iTETRIS implementation of ITG G5 has been realized by modifying the already available ns-3 classes modelling 802.11a MAC and PHY layers, and reusing the ns-3 modules emulating the 802.11e QoS mechanisms.

The resulting iTETRIS ITS G5A Communication Module depicted in Figure 4-13 includes all the needed communication functions required to operate in vehicular environments following the specifications of the standard [12]. The capability to simultaneously receive over the control channel G5CC and one of the G5A service channels is enabled by installing two ITS G5A NetDevices on vehicles and RSUs. Each ITS G5A NetDevice emulates a radio transceiver. One NetDevice always operates on the control channel (CC Netdevice), while the other one (SC Netdevice) switches among the two service channels G5SC1 and G5SC2. To allow transmissions in 10MHz-wide channels, the ITS G5A NetDevice required changes in the existing 802.11a PHY and MAC layers' implementation. ITS G5A transmissions on 10MHz-wide channels imply doubling all the OFDM timing parameters, and halving all the data rates compared to 802.11a. Considering this, new data rates from 3 to 27 Mbps for 802.11 half-clocked operations were implemented, along with modifications of various PHY and MAC timing parameters (e.g. the OFDM symbol interval, slot time and preamble length, etc). Setting up WiFi NetDevices to operate with ITS G5A 10MHz-wide channels can be made in a straightforward way by calling a unique function in simulation configuration phase.

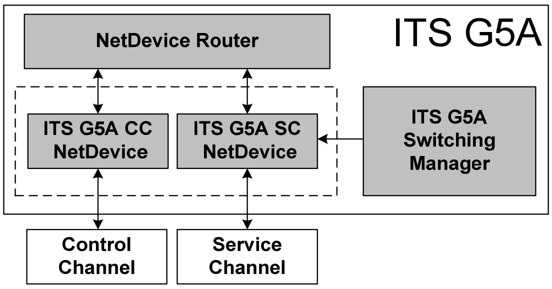


Figure 4-13. iTETRIS' ITS G5A communication module.

The iTETRIS ITS G5A implementation also provides the possibility for upper or management layers to control the transmission parameters of every single packet. For this purpose, a set of ns-3 packet tags were implemented. Each of these packet tags can specify the channel (ChannelTag), the transmission power (TxPowerTag) and the data rate (McsTag) used for the transmission of a packet. The set of packet tags implemented for iTETRIS ITS G5A NetDevices is depicted in Figure 4-14. A packet tag is only "virtually" attached to a packet and it is not transmitted. It is used by the ns-3 simulator to emulate certain operations whenever it is attached to the packet. These operations depend on the packet tag's type, and the value specified by the tag. For example, the TxPowerTag is used in iTETRIS to increase the transmission power of a packet transmission with respect to a minimum default value. The transmission power can be increased by a number of steps of 0.5dB as specified in the tag. In this way, the packet transmission power can be controlled exactly as specified in the standard [12].

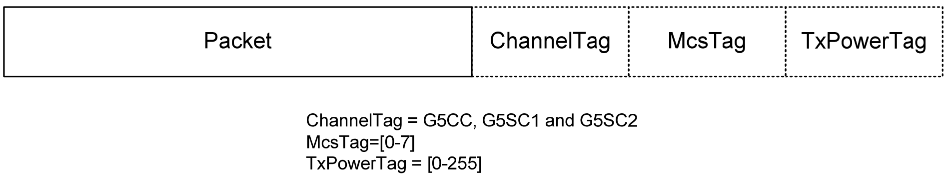


Figure 4-14. iTETRIS ITS G5A packet tags.

In iTETRIS, vehicles or RSU equipped with an ITS G5A radio interface can transmit a packet on different channels according to the value contained in the attached ChannelTag. In this context, packets coming from the Transport & Network layer should be correctly forwarded to one of the two installed ITS G5A NetDevices. To perform this forwarding function, the NetDeviceRouter was implemented. As depicted in Figure 4-13, the NetDeviceRouter is placed above the two installed ITS G5A NetDevices.

The ITS G5A NetDevice dedicated to the service channels (ITS G5A SC NetDevice) should be capable to switch between G5SC1 and G5SC2. As explained in Section 2.4, cooperative ITS service transmissions can be performed on one of the ITS G5A service channels. Such transmissions are advertised by means of Service Announcement Messages (SAMs) transmitted on the G5CC [30]. SAMs indicate the service channel over which service messages are going to be transmitted. On receiving nodes, one of the ITS G5A transceiver has to switch on the right service channel to receive these messages. Channel switches to receive a message on a given service channel may be needed while having pending packet transmissions on other service channels. In such conflicting cases, the service channel switching has to be performed based on application priorities, communications traffic load, user preferences, etc. Since the default ns-3 WiFi module was unable to perform channel switching, this capability was introduced in iTETRIS through the implementation of an ITS G5A Switching Manager (Figure 4-13). The channel switching capability implemented in iTETRIS consists of two implementations: a basic implementation and an extended implementation. The main difference between them is how pending packets scheduled for transmission on a specific service channel are managed when the ITS G5A SC NetDevice has to switch on another channel. In the basic implementation pending packets are dropped. In the extended implementation, these packets can be stored and transmitted later on. In this context, the ITS G5 Switching Manager provides functionalities such as the cancellation, suspension and resumption of packet transmissions interrupted due to a channel switch. The ITS G5 Switching Manager has been implemented as a separate module that can be attached to any ITS G5A NetDevice.

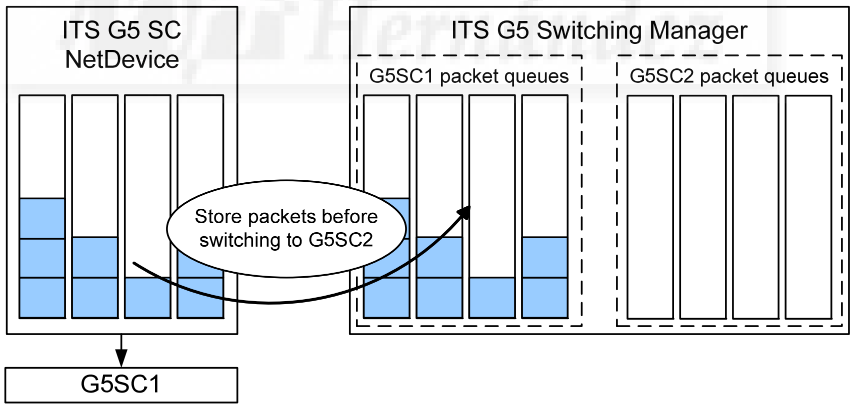


Figure 4-15. ITS G5 Switching manager operation.

The switching manager maintains a list of pointers to the EDCA packet queues of the NetDevice it is attached to. Through these pointers, the switching manager can obtain the currently enqueued packets and temporary store them in local buffers that are specific for a given SC. Let us consider the example of Figure 4-15, in which the ITS G5A SC NetDevice has to switch from G5SC1 to G5SC2. The packets scheduled to be transmitted on G5SC1 are currently in the EDCA queues. These packets can be temporarily stored in the ITS G5 Switching Manager for later transmission. After storing these packets, the EDCA queues of the NetDevice are emptied so that all the packets scheduled for the G5SC2 can be transmitted. At later instants, the packets in the ITS G5 Switching Manager can be reinserted in the EDCA queues, so that they can be transmitted on the G5SC1.

4.4.5.2 Optimized PHY modelling

iTETRIS introduces two important optimizations in the PHY layer modelling of the ETSI ITS G5A communication technology. This is done with to reduce the implementation complexity and therefore improve the simulation performance of large scale evaluations in terms of simulation execution time and computational resources expenditure. These optimizations concern the following aspects:

- *Interference range*. In the default ns-3 implementation, when a node transmits a packet on a given channel, the packet is processed for reception on all nodes having a NetDevice attached to that channel. This approach inefficiently consumes computational resources when applied to large scale simulations of vehicular communication environments. As explained in Sections 2.5.2 and 2.6, every vehicle and RSU periodically broadcasts standard CAM or beacon messages on the G5CC with a frequency ranging from 1 to 10Hz. In ns-3, every simulated vehicle and RSU has an ITS G5A NetDevice attached to this channel. As a result, every vehicle and RSU continuously process CAMs and Beacons transmitted by any other node in the simulation scenario independently on the distance separating transmitters and receivers. To address this inefficiency, the iTETRIS version of ns-3 introduces the use of a limited interference range. Only nodes within the interference range of the transmitter process the packet. In this thesis, the interference range has been selected as the distance at which the probability of packet detection is 10^{-4}, for the considered propagation model and maximum transmission power. By adopting this optimization, the number of vehicles processing transmitted packets is lower, and consequently the computational resources and simulation execution times are reduced.
- *Interfering packets list management.* In ns-3, a node maintains a list of interfering packets that is considered for the calculation of the total interference affecting a packet that is currently being received. The higher the number of packets stored in this list, the longer the simulation execution time. In the default ns-3 distribution, every time a new packet is sensed, it is appended to this packet list. Old packets that in theory would not overlap to the currently received packet are also kept in the list. To overcome this inefficiency, an optimization in the interfering packet list

management is implemented. This implementation keeps in the interfering packet list only those packets that are strictly needed for the calculation of the total interference.

Besides these optimizations, it is important to highlight that in ns-3 the probabilistic nature resulting from radio transmission effects is modelled by emulating the PER (Packet Error Rate) as a function of the Signal to Interference and Noise Ratio (SINR) [144]. To retrieve the probability P_{err} that the packet is received with any error, the following procedure is adopted. The bit error rate *BER(l)* on every packet interval *l* experiencing a constant SINR is computed. The *BER(l)* is derived from the SINR according to the adopted modulation and coding scheme. The SINR is computed considering the energy of the received packet and the sum of the receiver circuitry's noise (that is constant) plus the interference caused by other detected simultaneous transmissions. For each of the intervals *l,* the simulator determines $P_e(l)$ that is an upper bound of the probability that an error is present on the interval. The $P_e(l)$ is computed as a function of the *BER(l)* by considering an AWGN channel, the use of a binary convolutional coding (which is the case of 802.11p) and a Viterbi hard-decision decoding algorithm [145]. Knowing the probabilities $P_e(l)$ for every *l*, the P_{err} of the considered packet is finally computed as the probability that at least one of the intervals *l* contains an error. To decide whether the packet is correctly received or not, the computed P_{err} is compared to a random number drawn from a uniform distribution in the range [0-1]. If the number is greater than P_{err}, then the packet is considered to be successfully received.

4.4.5.3 Radio propagation modelling

Different studies have demonstrated that radio propagation effects significantly influence the operation and performance of vehicular communication protocols [47]. As a result, iTETRIS implements in ns-3 radio propagation models that aim at realistically reproducing such effects. After a careful review of the state of the art, iTETRIS selected from the available models those that more accurately take into account the characteristics of urban and highway scenarios for V2V and V2I communications. For V2V communications on highway scenarios, iTETRIS adopted the widely referenced Cheng & Stancil model [146]. At the time of the iTETRIS development, there were no specific channel models for urban V2V and V2I communications and highways V2I communications. For these communication scenarios, iTETRIS adopted the WINNER models developed for 5GHz cellular communications [147]. These models carefully reproduce the pathloss, shadowing and multipath fading effects. In addition, the urban models distinguish between LOS (Line-of-Sight) and NLOS (Non-Line-of-Sight) propagation conditions, since they significantly influence the received signal strength. Table 4-6 summarizes the models implemented in the iTETRIS version of ns-3, and

Figure 4-16 illustrates the pathloss differences for varying environments and communication types.

Scenario	**Urban**	**Highway**
V2V	WINNER B1 - Urban microcell [147]	Cheng & Stancil [146]
V2I	WINNER B1 - Urban microcell [147]	WINNER D1 – Rural [147]

Table 4-6. Radio propagation models adopted in iTETRIS.

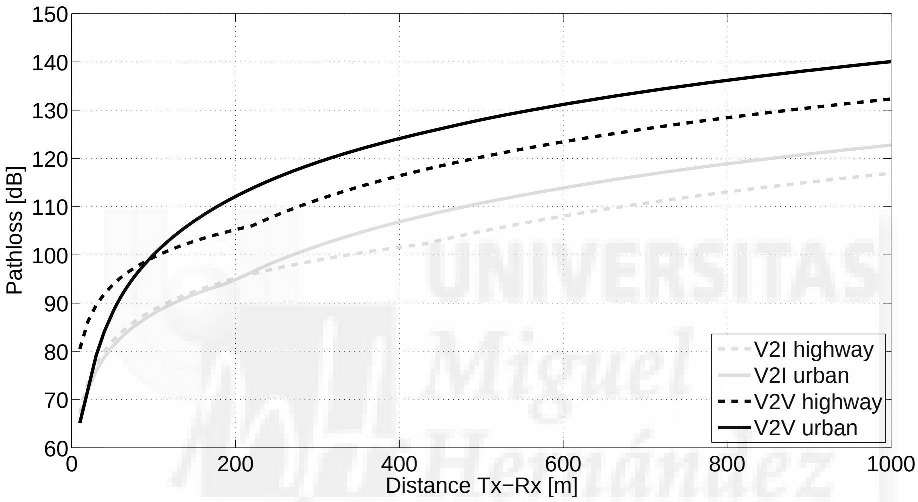


Figure 4-16. Pathlosses in iTETRIS for different environments and communication types.

The adopted models for pathloss, shadowing and small-scale fading are detailed in the following for V2V and V2I communications in urban environments.

Propagation modelling for V2V communications in urban scenarios

For urban V2V communications, iTETRIS implements the urban micro-cell propagation model developed in the European project WINNER (WINNER B1). Although WINNER B1 does not perfectly match V2V communication conditions (in this model, the minimum considered transmitting antenna height is 5 meters), it was considered the most adequate for urban scenarios due to its capability to differentiate between LOS and NLOS propagation conditions. The model used for the pathloss differentiates the visibility conditions between transmitter and receiver due to the presence of obstacles such as buildings. Under LOS conditions, its formulation is [147]:

$$PL_{LOS}(d) = \begin{cases} 22.7\log_{10}(d) + 41 + 20\log_{10}(f/5) & if \quad d < R_{bp} \\ 40\log_{10}(d) + 41 - 17.3\log_{10}(R_{bp}) + 20\log_{10}(f/5) & if \quad d \geq R_{bp} \end{cases} \quad (4\text{-}1)$$

where R_{bp} is the break-point distance (in meters) computed as:

$$R_{bp} = 4\frac{(h_A - 1)(h_B - 1)}{\lambda} \quad (4\text{-}2)$$

d is the distance (in meters) between transmitting and receiving vehicles, h_A and h_B are their respective antenna heights (in meters, set to 1.5m in this thesis to represent typical car heights), and f is the carrier frequency (in GHz). For NLOS conditions, the pathloss is expressed as:

$$PL_{NLOS}(d_A, d_B) = \min(PL_{NLOS}(d_A, d_B), PL_{NLOS}(d_B, d_A)) \quad (4\text{-}3)$$

with:

$$PL_{NLOS}(d_A, d_B) = PL_{LOS}(d_A) + 20 - 12.5n_j + 10n_j\log_{10}(d_B) \quad (4\text{-}4)$$

and where

$$n_j = \max(2.8 - 0.0024d_A, 1.84) \quad (4\text{-}5)$$

and d_A and d_B are the transmitter and receiver distances to the closest intersection, as illustrated in Figure 4-17.

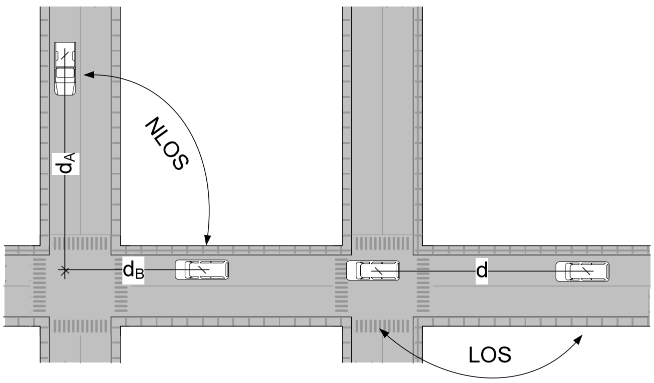


Figure 4-17. LOS and NLOS conditions between vehicles in urban scenarios.

As demonstrated in [47], there is a high difference between LOS and NLOS contributions of the pathloss calculated by this model (between 30 and 40 dB in average). This in turn causes that vehicles have a much higher communications range in LOS conditions compared to that achieved under NLOS conditions.

The shadowing propagation effect is normally modelled following a log-normal distribution with a zero mean and a standard deviation σ that depends on the considered environment. To represent the spatial correlation between the shadowing experienced by vehicles in nearby positions in urban scenarios, the Gudmundson model considering exponential autocorrelation function is adopted [148]. This model describes the correlation of the shadowing process at a distance *d* (in meters) as:

$$R_{yy}(d) = \sigma_s^2 \cdot \exp\left(-\frac{|d|}{d_S}\right) \tag{4-6}$$

where σ_S is the shadowing standard deviation and $d_S = D/ln(2)$, with *D* being the distance at which the normalised correlation is 0.5. This distance depends on the environment and is set to 20m following [149]. The shadowing standard deviation σ_S is set to 3dB for LOS and 4dB for NLOS propagation conditions [147].

The multipath fading effect resulting from the reception of multiple replicas of the transmitted signal at the receiver is also modelled. For LOS propagation conditions, a Ricean random distribution is adopted. To retrieve the Ricean envelope *r*, the following probability density function (PDF) is considered:

$$PDF(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right)I_0\left(\frac{Ar}{\sigma^2}\right) \tag{4-7}$$

where I_0 is the zero-order modified Bessel function of the first kind. The parameters *A* and σ (this σ is different from the shadowing standard deviation σ_S of equation (4-6)) are determined by the *K* factor (in dB) used to describe a normalized Ricean distribution that in turn depends on the distance *d* (in meters) between transmitter and receiver as follows [147]:

$$K = 3 + 0.0142d \tag{4-8}$$

On the other hand, under NLOS propagation conditions a Rayleigh random distribution is considered. This permits modelling the higher signal variations experienced under NLOS compared to LOS conditions [147]. The PDF considered to retrieve the Rayleigh envelope *r* is given by:

$$PDF(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{4-9}$$

As it can be seen, all of the above mentioned models depend on the LOS/NLOS conditions between communicating nodes. To retrieve such conditions, the iTETRIS version of ns-3 implements a basic visibility model. The aim of this model is to detect the visibility conditions between communicating nodes based on their relative position with respect to the buildings present in the simulated road network scenario. The presence of buildings is based on the urban road topology information extracted from the SUMO road network files introduced in Section 4.4. A visibility file with the coordinates of the walls forming the perimeter of the buildings present in the scenario is generated by consulting the considered SUMO road network. At the beginning of a simulation, this file is associated to the visibility model. In turn, the visibility model is set as a configuration parameter for the adopted propagation models. In the visibility file, each wall is represented as a segment. When the propagation models need a visibility condition calculation, the visibility model is called. The visibility model considers that there are NLOS conditions between two nodes if the segment connecting them intersects any of the walls present in the simulated scenario.

Propagation modelling for V2I communications in urban scenarios

The iTETRIS propagation model for V2I communications in urban scenarios corresponds to the WINNER B1 model presented in the previous section, the only difference being that an antenna height of 6m is used for a RSU (instead of 1.5m) in the equation (4-2). Apart from that, all the pathloss, shadowing, and small-scale fading parameters are the same as those provided for V2V communications.

4.4.6 Other radio access technologies

To achieve a satisfactory tradeoff between modelling accuracy and large scale simulation performance, different modelling solutions are adopted in the implementation of the iTETRIS communication technologies. From one hand, iTETRIS accurately models radio propagation effects as they considerably influence the operation and performance of cooperative applications and protocols. From the other hand, many system functionalities such as the network management and transmission control of the UMTS, WiMAX and DVB-H standards are simplified. In fact, iTETRIS is not aimed at investigating and optimizing the performance of such communication systems, but is rather designed to exploit their transmission capabilities to realistically and efficiently simulate cooperative ITS applications. Such simplifications do not negatively influence the simulation results.

4.4.6.1 WiMAX

The ns-3 WiMAX module of iTETRIS is built from an existing ns-3 implementation developed by INRIA [150]. While unicast and broadcast data transmission functionalities are accurately modelled, the implementation of WiMAX network management functionalities has been simplified. In this context, channel scanning, synchronization, and the process that WiMAX mobile stations periodically perform to get connected to a fixed WiMAX base station are emulated by consulting an Infrastructure Location Map containing the position of fixed stations. A similar approach has been followed for the dynamic adaptation of the mobile stations' modulation, coding and transmission power. For this purpose, an Adaptive Modulation & Coding (AMC) Map is defined to assist in the decision process. The dynamic parameters are selected based on the distance between mobile stations and the fixed stations to which they are attached, and on the current radio channel conditions. Finally, Command Managers (attached to each WiMAX node) are included to simulate the transfer of control information between mobile and base stations for management and maintenance of the WiMAX network. As a result, the registration and connection establishment processes are performed through the exchange of primitives and without simulating the transmission of any control message, which implies simulation time and memory resources gains.

4.4.6.2 UMTS

The UMTS cellular technology has been used in this thesis to support the hybrid V2X vehicular dissemination scheme proposed in Chapter 7. The implementation of UMTS in the ns-3 version of iTETRIS has followed a similar process to that adopted for WiMAX. Based on an existing UMTS implementation, those aspects that would influence the outcomes of the considered investigations are accurately modelled and implemented, while those that are more related to the management of UMTS networks are simplified. The resulting UMTS implementation is built from the UMTS module developed at the University of Strathclyde, and originally implemented in ns-2 [151]. As in the original implementation, two NetDevices are implemented, one for the UEs (User Equipments, in this case corresponding to vehicles equipped with UMTS access) and another one for UMTS base stations (Node B). To reduce the complexity of the original UMTS architecture's implementation, the iTETRIS version of ns-3 assigns to an UMTS Node B all the necessary intelligence and functionalities of the RNC (Radio Network Controller). Moreover, an UMTS Manager class is defined and implemented to model control procedures such as handovers or the setup of new connections. This entity is in charge of processing the demands related to the control level, and maintains a list of pointers to all the Nodes B deployed in the simulated scenario. When the UMTS Manager receives a petition to perform any control function (e.g. a setup request to a certain Node B), it notifies the petition to the RRC (Radio Resource Control) layer of the corresponding Node B and forwards the response to the originator UE node.

4.4.6.3 DVB-H

The ns-3 version of iTETRIS implements a new simplified DVB-H module that is not based on any existing ns-3 or ns-2 implementation. The implementation differentiates between two types of nodes. The DVB-H Base Station is in charge of the management and delivery of data services. The DVB-H User Equipment represents the consumer of DVB-H data services (a vehicle equipped with a DVB-H receiver in this case). The implemented DVB-H NetDevices include three different levels, each of them modelling different functionalities as defined by the DVB-H standard. The upper layer is referred to as the DVB-H Manager, and is mainly in charge of operations related to the creation and management of services, management of the network resources, and establishment and maintenance of connections between base and mobile stations. The Link Layer is devoted to the creation and processing of MPE-FEC (Multi-Protocol Encapsulation–Forward Error Correction) sections and PSI/SI (Program-Specific Information, and Service Information) tables, and the operation of the time slicing functionality. Finally, the Physical Layer handles the transmission and reception of MPEG-2 Transport Streams, and the creation and processing of OFDM blocks, in addition to the estimation of the PER experienced during DVB-H transmissions.

4.5 Summary and discussion

This thesis adopts computer simulations for the evaluation of the proposed routing and dissemination protocols. Considering the large scale nature of these protocols, simulation offers a good tradeoff between modelling accuracy, scalability, and repeatability of the evaluations. Simulation is also the technique that permits generating different evaluation scenarios in the fastest and easiest way. The simulation results described in this thesis have been obtained through the open source iTETRIS simulation platform. The author of this thesis contributed to the design and development of iTETRIS. iTETRIS combines wireless communication and vehicular mobility simulation capabilities. This is achieved by integrating the ns-3 network simulator, the SUMO traffic simulator, and the implementation of cooperative ITS applications (iAPP) in a very modular way. Through this integration, iTETRIS can effectively emulate the mutual dependence between vehicular mobility, wireless communications, and cooperative ITS applications. The accuracy of iTETRIS' simulation outcomes is guaranteed by the validated models of its integrated wireless and traffic simulators. Compared to other similar integrated simulation platforms, iTETRIS provides interesting advances. iTETRIS permits implementing and evaluating cooperative ITS applications in a fully modular and language-agnostic way. This is achieved thanks to the iTETRIS' open interfaces that abstract application developers from the internal implementation of the platform. iTETRIS' does not couple its traffic and wireless simulators directly, but rather uses a middleware. In this way, the integrated simulators can be independently modified, extended, or even replaced separately and independently, which provides iTETRIS increased sustainability and capability for evolution. iTETRIS has extended the default release of the ns-3 wireless simulator in order to implement a communication stack compliant with the ETSI standards for Intelligent Transport Systems Communications. This iTETRIS' distinguishing feature allows the standard compliant implementation and evaluation of the protocols presented in this thesis. iTETRIS' large scale simulations of these protocols are enabled by intelligent implementation and modelling solutions, especially in the wireless simulation part. Such solutions are integrated in the platform thanks to the open source availability of its code.

5

Multi-hop Road Connectivity Characterization

Cooperative applications aimed at delivering information to distant destinations can make use of multi-hop transmissions through intermediate relaying vehicles in the VANET. The effectiveness and efficiency of these applications highly depend on the routing protocols adopted to select routes of intermediate forwarders. Different types of vehicular GeoRouting protocols have been presented in the literature. These protocols have evolved towards approaches that select forwarding paths based on the knowledge of real time road traffic conditions. Real time road traffic conditions are used by these protocols to retrieve the potential presence of relaying nodes over candidate forwarding paths. In this context, the most commonly used road traffic information is the vehicular density. Under the assumption that the most travelled roads are the most suitable to support reliable end-to-end multi-hop transmissions, some approaches compute and share in the VANET the vehicular density of the road segments forming the routing scenario. By holding an up-to-date awareness of candidate road segments' density, vehicles can perform effective routing decisions. However, these approaches usually imply a high communications overhead that can compromise the effectiveness of multi-hop transmissions, and negatively affect coexisting cooperative applications. To solve the limitations of these schemes, this chapter introduces DiRCoD, a novel Distributed and Real Time Communications Road Connectivity Discovery mechanism. As demonstrated in the following, DiRCoD can support the operation of routing protocols requiring a real time characterization of road segments' capability to support multi-hop transmissions. However, and differently from approaches based on vehicular density, DiRCoD is based on the direct estimation of roads' multi-hop connectivity. Estimating the multi-hop connectivity of road segments requires a lower communications overhead and implementation cost. Vehicular routing protocols considering DiRCoD's multi-hop road connectivity as decision metric are expected to better administrate the channel resources. This feature can support the implementation of future cooperative multi-application scenarios in a better way.

The rest of this chapter is organized as follows. Section 5.1 introduces the motivations of using real time traffic information to drive vehicular routing decisions, and explains the advantages of considering multi-hop road connectivity instead of vehicular density. Section 5.2 presents DiRCoD in a generic way, and provides some useful definitions to understand its functioning and operation. Section 5.3 provides the details of DiRCoD's operational implementation. Section 5.4 describes IFTIS, a state of the art mechanism estimating the vehicular density of road segments. IFTIS is used as a benchmark to evaluate DiRCoD's performance reported in Section 5.5. Finally, Section 5.6 provides a short summary and some discussions.

5.1 Motivations

As explained in Section 3.2.2, various vehicular GeoRouting protocols have been proposed in the literature for the forwarding of messages in VANETs. At the time of conducting this study, particular relevance was hold by approaches that divide the routing process in two steps. The first one is the "macroscopic" selection of a geographical forwarding path connecting source and destination nodes. A geographical forwarding path consists of a set subsequent geo-referenced anchor points that a message has to traverse to reach its final destination. The second step is the "microscopic" selection of forwarding nodes over the geographical area separating two subsequent anchor points. Examples of this approach are A-STAR [51], VADD [52], LOUVRE [54], and GyTAR [57]. All these protocols apply the above mentioned two steps-process over road networks where the anchor points are road intersections interconnected by road segments. In order to provide packet routing with reliability and speed, all these approaches use the knowledge of the vehicular density in the considered road network. These protocols assume that road segments experiencing higher vehicular density provide a higher number of forwarders, and hence can support more reliable multi-hop transmissions. To exploit such property, these routing mechanisms select geographical forwarding paths composed by the most travelled road segments. Approaches like A-STAR and VADD assume to know the vehicular density of all the road segments forming the road network. However, these densities derive from traffic statistics. Although taking into account daytime/nightime variations or rush hour characterizations, this road density characterization can be defined static. In fact, this characterization would not be updated in case of unexpected changes of the vehicular traffic flows, and therefore might not represent the actual density of road segments at every moment. To overcome the limitations of this approach, mechanisms like LOUVRE and GyTAR make use of real time vehicular density information. In this case, the vehicular density of road segments is cooperatively computed and updated by vehicles. This information is distributed in the VANET so that vehicles can operate routing decisions that dynamically adapt to the actual status of the road traffic. With LOUVRE, vehicles broadcast messages carrying the IDs of the vehicles met in the road segment they are driving on. The density of a road is computed by counting the number of unique IDs overheard. The densities of already traversed road segments are also periodically broadcasted by vehicles. In this way, LOUVRE proactively generates and shares a sort of road network density map that is reused to drive its routing decisions. The GyTAR proposal computes road densities by running the distributed IFTIS protocol [58]. IFTIS uses dedicated GeoNetworking messages carrying the instantaneous vehicular density "probed" over adjacent portions of a road segment. By receiving these messages at road intersections, vehicles are informed about the density of adjacent road segments, which is useful for driving the selection of geographical forwarding paths.

As demonstrated by the discussed examples, cooperatively computing and distributing the vehicular density generally requires non-negligible additional communications overhead. Although LOUVRE and IFTIS present countermeasures aimed at ensuring the scalability of their solutions, limiting the communications overhead is a key target to ensure the correct operation of cooperative applications. As the many studies on vehicular channel congestion control demonstrate ([152] and [153] only to cite a few), an efficient utilization of the channel resources is indeed a primary issue in VANETs. In this context, routing approaches based on channel-demanding vehicular density characterizations might not represent the most convenient solution. Moreover, using vehicular density as a metric to drive geographical forwarding path selections might result in that packets are forwarded over the most travelled road segments. Over these roads, the number of vehicles simultaneously transmitting CAM or beacon messages, and in general performing cooperative communications, is greater. As a result, forwarding packets over these roads increases the probability of channel congestion.

In this context, this thesis proposes DiRCOD, a Distributed and Real Time Communications Road Connectivity Discovery mechanism used to assesses the multi-hop road connectivity. The multi-hop road connectivity is defined as the capability of a road segment to support reliable multi-hop transmissions along its length, independently from its vehicular density. A road segment is multi-hop connected if it contains a sufficient number of nodes (vehicles or RSU) distributed in such a way to permit that messages can be forwarded without interruptions from its beginning to its end. The example depicted in Figure 5-1 shows that a road segment (e.g. I_1-I_2) can be multi-hop connected without necessarily experiencing high vehicular density. In the selection of geographical forwarding paths, a vehicular routing protocol based on multi-hop road connectivity would consider two candidate multi-hop connected road segments in the same way, irrespectively of the experienced vehicular density. To better understand this concept, let us consider the scenario depicted in Figure 5-1, where a message has to be transmitted from vehicle S to the destination D. A routing protocol based on vehicular density information would always transmit the message over the geographical path including road segment I_1-I_3. As a result, it would increase the probability to experience or cause channel congestion over this road. On the contrary, a routing protocol based on multi-hop road connectivity would not discard the possibility to forward the message over I_1-I_2, and thus would reduce the probability to overload I_1-I_3. Considering multi-hop road connectivity as a decision metric permits vehicular routing protocols to distribute the communications overhead over the road network in a more uniform way. In addition, estimating the multi-hop road connectivity can be performed by DiRCoD in a much more channel-efficient way compared to techniques assessing the vehicular road density. Compared to these techniques, DiRCoD does not need additional dedicated transmissions, but rather relies on standard beacon messages.

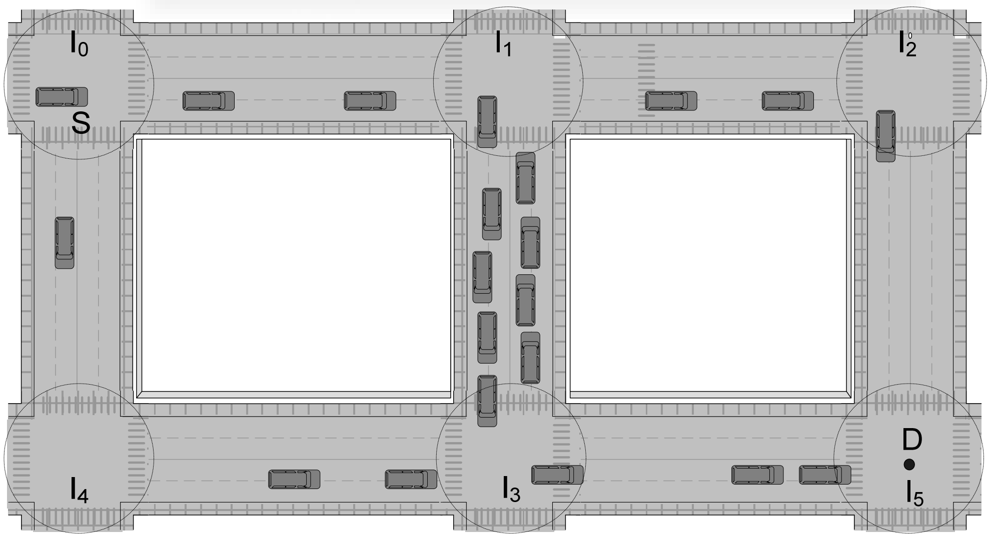


Figure 5-1. Example of vehicular routing scenario.

5.2 DiRCoD concept

This section introduces the general concept of the DiRCoD mechanism. In order to correctly understand DiRCoD's principles and operation some preliminary definitions on the used road network representation are needed.

5.2.1 Road network representation

DiRCoD considers that road networks can be schematically represented as sets of road segments delimited by anchor points. An intuitive way to retrieve a road segments' representation from a generic road network is to consider anchor points as road intersections. An example of resulting road network representation is depicted in Figure 5-1, where every road segment can be identified by the delimiting pair of intersections (e.g. I_1-I_2). To indicate the direction in which a message is transmitted, the symbol "→" is adopted. As an example, the transmission of a message from intersection I_1 towards intersection I_2 is indicated as a message forwarding in the direction $I_1 \rightarrow I_2$. To complete the characterization of the road network representation, "intersection zones" are defined as circular regions of radius *R* centered at road intersections (circles in Figure 5-1). Vehicles in these zones are considered to hold radio visibility conditions permitting them to better communicate with vehicles placed over adjacent road segments. For this reason, intersection zones are considered in this thesis to be the regions in which vehicles can optimally sense the connectivity conditions of adjacent road segments to operate geographical forwarding path decisions. In this thesis, it is considered that vehicles hold a knowledge of the above mentioned road network representation through the use of digital maps. Moreover, vehicles are considered to use GPS systems to retrieve and update their position with high precision and frequency. GPS devices allowing a precision of less than one meter and an update frequency of 20Hz are nowadays available and are likely to be integrated on vehicles in the future to allow a correct operation of vehicular cooperative applications [154][155].

5.2.2 Principles and operation

As discussed in Section 3.2.2, a number of vehicular routing protocols statically select geographical forwarding paths without considering their actual capability to support multi-hop transmissions. Contrary to these schemes, DiRCoD supports routing approaches that try to iteratively select, at subsequent road intersections, the road segments providing a higher capability of message forwarding. To support such selection, DiRCoD estimates the multi-hop road connectivity. Considering the example illustrated in Figure 5-1, let us suppose that vehicle S at intersection I_0 needs to transmit a message to all the vehicles placed around point D at intersection I_5. When the transmitted packet reaches intersection I_1, the receiving node has to instantaneously decide whether it is more convenient to route the packet towards I_2 or I_3. To assist this type of dynamic routing decisions, DiRCoD provides a measure of the multi-hop connectivity of the candidate road segments respectively in the directions $I_1 \rightarrow I_2$, and $I_1 \rightarrow I_3$. To explain DiRCoD's operation, let us consider the scenario depicted in Figure 5-2, that represents the road segment delimited by the intersections I_1 and I_2. In the depicted scenario, vehicle E entering I_1 needs to be informed about the connectivity status of the road segment in the direction of I_2 (direction $I_1 \rightarrow I_2$) to decide whether to forward a packet in this direction or not. As previously explained, a road segment is defined to be multi-hop connected if it contains a sufficient number of spatially distributed vehicles to forward packets from one end of the road segment to the other end. If this is the case (Figure 5-2a), the packet would be forwarded directly to I_2 through multi-hop transmissions. In case of partial multi-hop connectivity (Figure 5-2b), a packet transmitted from I_1 could not be forwarded up to I_2, but would only reach a vehicle placed at a given distance from I_2. To quantify this remaining distance and thereby the connectivity status of a road segment, DiRCoD defines the "*virtual distance*" metric separating I_2 from I_1. The lower the virtual distance, the better the multi-hop connectivity. To estimate the virtual distance, DiRCoD considers that the road segment is divided into *"road sections"* numbered with increasing values depending on their distance from I_2 (see Figure 5-2). Each of these sections has a length equal to vehicles' communications range. Radio propagation results in that it is not possible to define a communications range deterministically. The capability for two nodes to successfully communicate with each other at a given transmission power and distance can only be described in probabilistic terms. In the context of this thesis, the communications range (and hence the length of DiRCoD's road sections) has been defined as the distance at which two vehicles under Line-of-Sight (LOS) propagation conditions successfully exchange 99% of the transmitted beacons. With this assumption, DiRCoD defines the virtual distance separating I_1 from I_2 as the number of road sections between I_2 and the closest vehicle to I_2 that can be reached from I_1 directly through multi-hop transmissions. Formally, DiRCoD defines the virtual distance as the number of road sections (or hops) between I_2 and the closest vehicle to I_2 that can be reached from I_1 through multi-hop transmissions. In Figure 5-2b, the virtual distance evaluated at I_1 is 2 hops since a packet transmitted from I_1 would only reach vehicle B that is placed at 2 hops from I_2. This road connectivity status is defined as *"partial multi-hop connectivity"* On the contrary, Figure 5-2a illustrates a road segment with *"full multi-hop connectivity"*. In this case, the virtual distance separating I_2 from I_1 is 0 since a packet can multi-hop forwarded from I_1 to I_2.

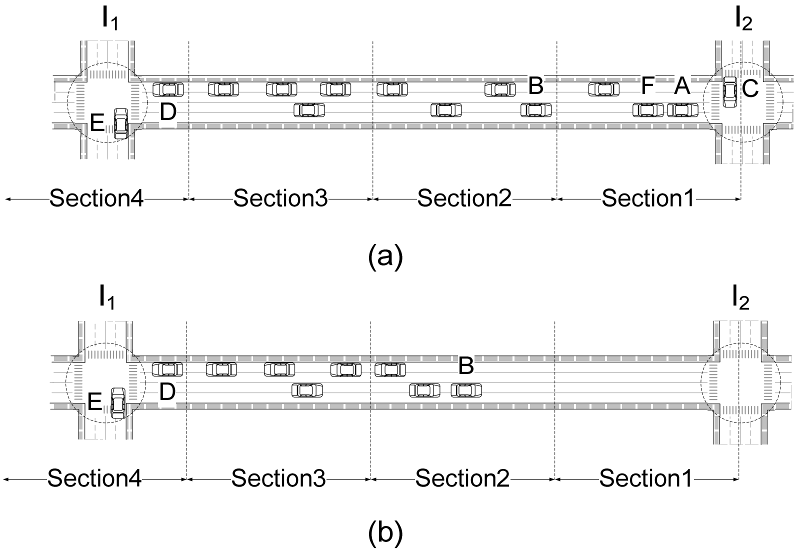


Figure 5-2. Road segment with DiRCoD full multi-hop connectivity (a), and DiRCoD partial multi-hop connectivity (b).

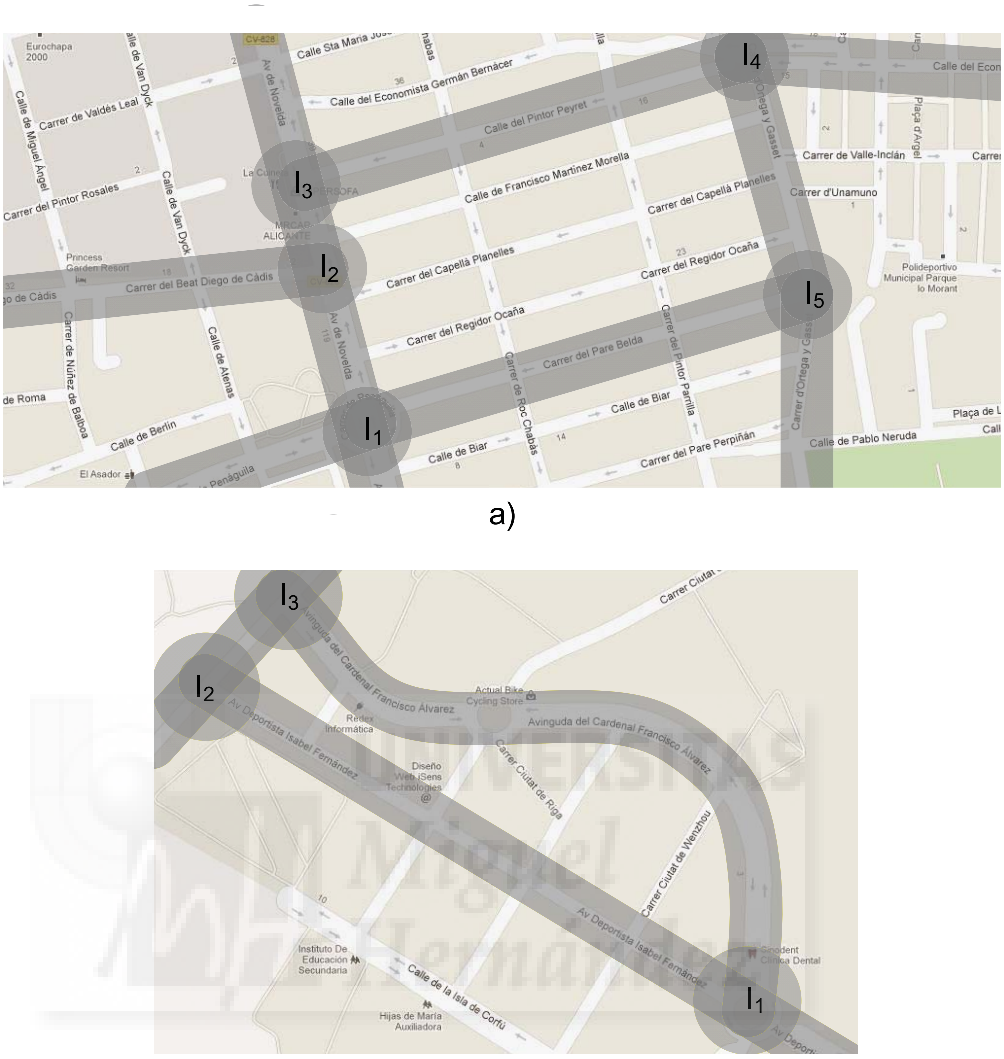
To dynamically inform vehicles entering intersection I_1 about the connectivity status of a road segment in a given direction ($I_1 \rightarrow I_2$ in Figure 5-2), DiRCoD includes the above defined virtual distance information into a *"Connectivity Field"* (*CF*). The connectivity field is appended to standard beacon messages periodically transmitted by vehicles every T_{Beacon} seconds (See Section 2.5.2). The resulting beacon's representation is depicted in Figure 5-3.

Figure 5-3. Standard beacon message with an appended DiRCoD's *Connectivity Field*.

It is important to note that DiRCoD's *CFs* are eventually appended to beacon messages only by vehicles placed in the inner part of a road segment. Vehicles placed in the intersection zones (depicted in Figure 5-2 as circular regions centered at intersections) do not append *CFs* to their beacons. A vehicle appends a *CF* indicating the road section it is placed at, unless it detects (by consulting its location table) that other vehicles are closer to I_2 or are in the intersection zone of I_2. In the scenario depicted in Figure 5-2b, vehicle B does not detect any other vehicle closer to I_2. As a result, upon the expiration of the periodic timer T_{Beacon}, it appends to its beacon message a *CF* indicating a virtual distance of '2'. In fact, vehicle B would need two hops to reach vehicles in I_2 intersection zone. In the scenario depicted in Figure 5-2a, vehicle F would initially append a *CF* with a virtual distance of '1' to its beacon message, given its location in road section 1. However, since it can detect the presence of vehicle C at I_2 (vehicle C is listed in its location table), vehicle F appends a *CF* indicating a virtual distance of '0'. Similarly, vehicle B placed at section 2 in Figure 5-2a would initially append a *CF* of '2' in its beacon. However, it does not append this *CF* since it detects the presence of vehicle F. On the contrary, vehicle B appends a *CF* equal to '0' upon receiving from vehicle F a beacon carrying a *CF* with this virtual distance. Through this sequential process, DiRCoD *CFs* are forwarded towards I_1. In the example depicted in Figure 5-2a, the vehicles at I_1 will receive a beacon message with a *CF* of '0' indicating full multi-hop road connectivity. A *CF* of '2' indicating partial multi-hop connectivity will instead be received at intersection I_1 in the example of Figure 5-2b, given that the closest vehicle to I_2 is two hops away from this intersection.

Two important considerations are necessary concerning the applicability of DiRCoD in real world scenarios. The first consideration is that to apply DiRCoD, it is not necessary to use a representation including all the possible road segments and intersections. Let us consider the urban scenario depicted in Figure 5-4a. If the road network was decomposed considering all the possible intersections, the resulting representation would consist of very short road segments and closed-by intersection zones. The computational cost that a vehicle would require to map its position, and refresh road connectivity information over such representation would be higher. Moreover, such a detailed representation would be redundant for GeoRouting protocols operating routing decisions at intersections. Repeating the dynamic selection of the next forwarding direction at every single intersection would imply higher and unnecessary delays. An example of more suitable road network representation for GeoRouting protocols using DiRCoD is depicted in Figure 5-4a. In this figure, the road segments and intersections considered for DiRCoD representation are highlighted in dark grey. Secondary road segments that are too narrow and that are seldom if ever traveled can be excluded. The road segments chosen for DiRCoD representation converge into road intersections that can be selected based of their capability to accommodate traffic flows coming form different directions. These intersections are the most suitable to operate dynamic routing decisions.

The second consideration is that DiRCoD can be applied independently of the shape of the roads forming the vehicular routing scenario. In fact, although DiRCoD's operation has been explained so far by considering straight road segments, its functioning would not change in cases like the one depicted in Figure 5-4b, where two intersection zones (I_1 and I_3) are connected by a curved road segment. Even considering a curved road, if vehicles are adequately placed to forward DiRCoD's *CFs*, the full or partial multi-hop road connectivity information can be notified at intersections.



a)

b)

Figure 5-4. Possible DiRCoD representations of real road network scenarios.

5.3 DiRCoD implementation

5.3.1 Connectivity field forwarding

Section 5.2.2 has explained that the multi-hop connectivity status of a road segment is represented by DiRCoD in terms of a virtual distance separating the two delimiting intersections. In the example depicted in Figure 5-2, the virtual distance in the direction $I_1 \rightarrow I_2$ has to be delivered at intersection I_1. The virtual distance information is generated by a vehicle placed over the road segment, included in a *CF*, and appended to a broadcast beacon message. Given the direction of the connectivity estimation, this connectivity field is indicated by CF_{12}. By subsequently including the overheard *CF* in their beacons, vehicles forward the virtual distance information towards intersection I_1. However, if all the vehicles along the road segment appended a *CF* to their beacons, DiRCoD would generate redundant connectivity estimates, which could compromise its scalability. To limit the inclusion of *CFs* in beacon messages, DiRCoD adopts specific mechanisms based on timers and vehicle positions. A first mechanism is aimed at selecting one vehicle (among those receiving a beacon with an appended *CF*) for it to be the only forwarder of the *CF* towards I_1. This selection is performed by vehicles in a distributed way following a contention-based mechanism similar to that presented by the CBF forwarding protocol [45]. All the vehicles placed on the road segment I_1-I_2 and receiving a beacon with an appended *CF* (or a beacon from a vehicle placed at I_2's intersection zone) activate a timer T_1. The duration of this timer is inversely proportional to the progress towards the center of I_1 with respect to the position of the beacon's sender. The closest vehicle to I_1 will see its timer T_1 expiring first. Upon T_1 expiration, this vehicle broadcasts a beacon message with a *CF* appended, and schedules the transmission of the next beacon in the next T_{Beacon} seconds. Upon overhearing the *CF*, the other vehicles with timer T_1 active abort the inclusion of a *CF* in their beacon messages. The formula adopted by DiRCoD for the calculation of T_1 is reported by equation (5-1). The formula is schematically represented in Figure 5-5, which in turn reconsiders the configuration of Figure 5-2b. Vehicle B broadcasts a beacon with a *CF* appended. Upon receiving this beacon, all the vehicles activate a timer T_1. The duration of T_1 (in seconds) on vehicle F is:

$$T_{1F} = T_{\max}\left(1 - \frac{p_F}{p_{\max}}\right) \tag{5-1}$$

where p_{max} (in meters) is equal to the maximum distance at which a vehicle is expected to receive beacons from vehicle B, and therefore corresponds to the maximum progress that a vehicle can provide for the *CF* forwarding towards I_1. T_{max} (in seconds) is the maximum duration of timer T_1 allowed by the protocol. The progress p_F is computed as:

$$p_F = d_{B-I1} - d_{F-I1} \tag{5-2}$$

being d_{B-I1} and d_{F-I1} the distances (in meters) separating vehicles B and F from I_1, respectively. To calculate these distances, vehicle F retrieves the position of B from the common header of the received beacon (see Section 2.5.2), and the position of I_1 from the digital map. In case distance d_{F-I1} was higher than d_{B-I1}, vehicle F would not provide progress for the *CF* forwarding towards I_1, and consequently the timer T_1 would not be activated. As Figure 5-5 shows, among the vehicles receiving the *CF* from vehicle B, vehicle F provides the highest progress towards I_1. Therefore, it is the only vehicle forwarding the *CF* in its beacon.

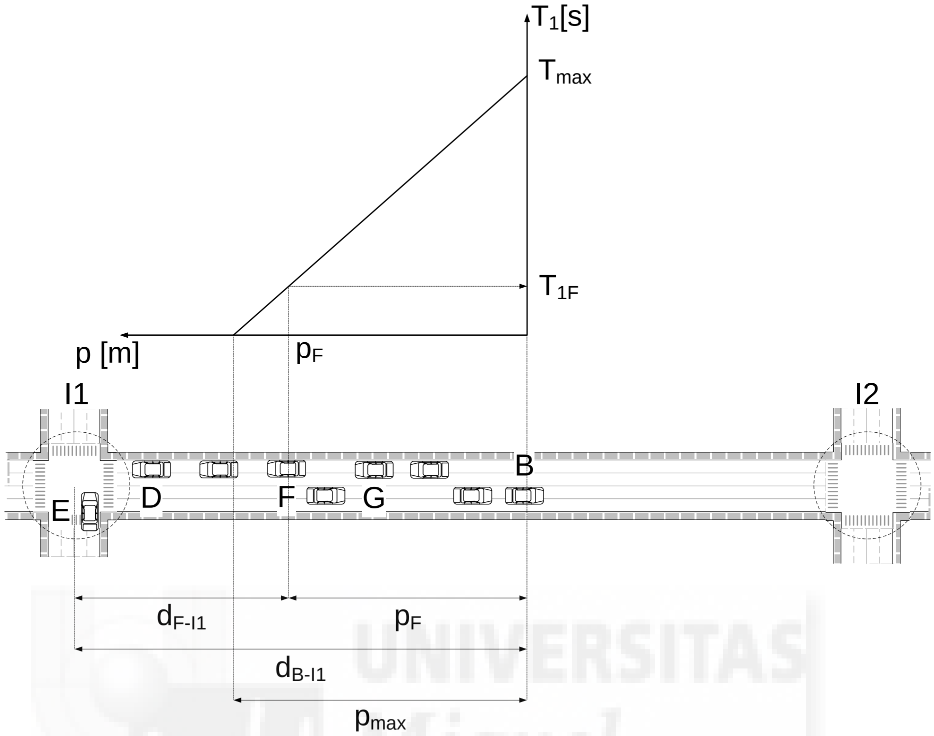


Figure 5-5. DiRCoD's *CF* forwarding timer T_1.

The same contention process is operated by vehicles in the configuration depicted in Figure 5-2a. Here, the timer T_1 is activated on vehicles upon receiving a beacon from a vehicle C at intersection I_2. Differently from the previous case, the expiration of this timer does not result in a *CF* forwarding, but rather in a *CF* generation. In this case, the vehicle that sees its timer T_1 expiring first generates a *CF* with a virtual distance of '0'. This *CF* is appended to a beacon message that is immediately broadcasted. In fact, as explained in Section 5.2.2, vehicles at intersection zones do not append any *CF* to their beacons. The generation and forwarding of *CFs* is only performed by vehicles placed in the inner parts of road segments.

5.3.2 Connectivity field generation period

Letting only one vehicle generate or forward *CFs* certainly reduces the amount of communications overhead required by DiRCoD. To further improve its channel efficiency, DiRCoD also defines a method to control the period between two consecutive transmissions of road connectivity estimates. Upon receiving a beacon with a *CF* appended, or a beacon from a vehicle at I_2, vehicles activate another timer indicated as T_2.

The duration of T_2 is referred to as "*Connectivity Field generation period*", and indicates the time that vehicles have to wait before being allowed to generate or forward new *CFs*. Considering Figure 5-2a, if more vehicles were present in the intersection I_2, the vehicles placed in the inner part of the road segment would receive different beacon messages over short time intervals. If a timeout like T_2 was not adopted, the reception of these beacon messages would make vehicles in the road segment generate *CFs* with a relatively high frequency. Appending these *CFs* to beacon messages would imply redundant connectivity data generated at short periods and a consequent waste of communication resources. To avoid this effect, the vehicles in the road segment generate or forward new *CFs* only if a previously activated T_2 has expired, which means not earlier than *CF generation period* seconds. The definition of the *CF generation period* could be done based on the vehicular traffic variations to control or reduce the communications channel load. In particular, if the vehicular traffic over a road segment does not vary very rapidly, the multi-hop connectivity status measured in terms of DiRCoD's virtual distances is expected to stay stable for a few seconds (2 or 3s, as it is demonstrated in the following). As a result, there is no need to perform DiRCoD's multi-hop connectivity estimations with higher frequency, and the *CF generation period* can be set to higher values to save channel resources.

5.3.3 Neighbours reliability estimation

The operation of DiRCoD relies on vehicles' capability to exchange beacon messages and recognize whether neighbour nodes are currently present over the road segment. Considering Figure 5-2a, it has explained that vehicle B does not generate a *CF* with value '2', if it detects that neighbour vehicles closer to intersection I_2 are present. Vehicle B detects neighbour nodes by consulting its location table. According to current ETSI definitions, a vehicle stored in the location table is considered a "neighbour" if a beacon or any other GeoNetworking message has been recently received from this vehicle [33]. However, radio links are characterized by rapidly varying signal levels as a result of multipath fading. In this context, beacon messages could be instantaneously exchanged by two vehicles without implying that a reliable radio link could be guaranteed between them. Moreover, if a vehicle is stored in the location table for a prolonged time, it could be still considered a neighbour when actually it is not. These effects, if not adequately addressed, could negatively affect the operation of DiRCoD, and result in incorrect multi-hop road connectivity estimates. To avoid this, a neighbour reliability mechanism is introduced in DiRCoD. This work considers a beaconing rate of 2Hz (and hence a T_{Beacon} of 0.5s). In this context, a neighbour is considered "*reliable*", if at least 4 beacons have been received from this node in the last 4s, with the last beacon reception being not older than 1s. Referring to Figure 5-2, a vehicle generates or forwards a DiRCoD's *CF* only upon receiving beacons from a reliable neighbour closer to I_2. If no reliable neighbours closer to I_2 are detected, a vehicle generates a *CF* carrying the value corresponding to the road section it is placed at (e.g. vehicle B broadcasts a beacon carrying a *CF* indicating a virtual distance of '2').

5.3.4 Bidirectional connectivity estimation

So far, the DiRCoD mechanism has been described considering only one direction, i.e. multi-hop connectivity estimates at I_1 for the road segment in the direction $I_1 \rightarrow I_2$. However, DiRCoD has to be executed simultaneously for both directions of a road segment. This is necessary to support possible routing decisions at I_1 as well as at I_2. The DiRCoD mechanism is capable to support bidirectional multi-hop connectivity assessments as follows. At the moment of generating or forwarding a connectivity field referring to the direction $I_1 \rightarrow I_2$ (CF_{12}), a vehicle also operates a DiRCoD connectivity assessment in the opposite direction. If all the conditions for the generation of a connectivity field CF_{21} referring to the direction $I_2 \rightarrow I_1$ hold (absence of closer reliable neighbours to I_1, and timer T_2 inactive), a beacon message with two *CFs* (one per direction) is broadcasted. Otherwise, the connectivity assessment for $I_2 \rightarrow I_1$ is performed separately. Figure 5-6 shows a flow diagram representing the process used by DiRCoD to generate and forward a *CF* referring to the direction $I_1 \rightarrow I_2$, and eventually include a *CF* referring to the direction $I_2 \rightarrow I_1$. This figure shows that generation and forwarding of a *CF* are respectively triggered by two events: the expiration of the periodic timer T_{Beacon}, and the reception of a beacon message with an appended *CF*. These two events are represented as shaded blocks in the flow diagram.

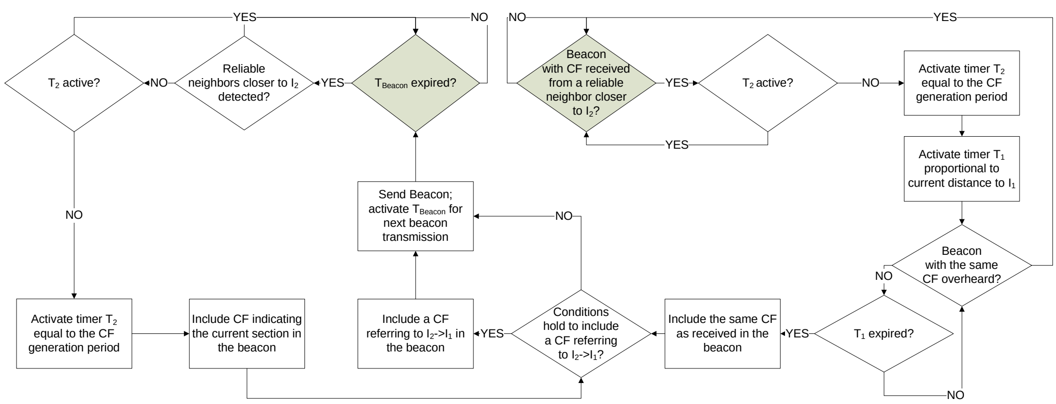


Figure 5-6. Flow diagram for the generation and forwarding of DiRCoD's *CFs* (direction $I_1 \rightarrow I_2$).

5.3.5 Connectivity field structure and processing

To complete the description of the DiRCoD proposal, it is important to describe the format of the connectivity field appended to standard beacon messages. The size of this field can be set to a few bits. In this work, *CFs* of one byte have been used. Considering the examples of Figure 5-2, the first bit is used to distinguish whether the connectivity field refers to the direction $I_1 \rightarrow I_2$, or the direction $I_2 \rightarrow I_1$. The remaining seven bits are used to quantify the multi-hop connectivity of the road segment in terms of DiRCoD's virtual distance. According to the definitions of Section 5.2.2, if the considered communications range was 100m, the remaining 7 bits would be enough to represent the virtual distance on road segments having a length up to 12.7km. It is important to remark that the size of the connectivity field has to be tuned according to the operational conditions. 7 bits to code the virtual distance are a very conservative value, especially in urban road network scenarios, where the adopted road segments are supposed to be shorter than 12km.

To identify the road segment that a connectivity field refers to, it is not required to include additional information in DIRCoD's *CFs*. When a vehicle overhears a *CF*, it infers this information from the position of the vehicle transmitting the *CF*, which is always included in standard beacon messages. By mapping this position on the digital map's road network representation, the vehicle can easily derive the road segment. When a vehicle is in the inner part of a road segment, it discards DiRCoD's *CFs* received from vehicles placed in other road segments. It only processes *CFs* transmitted from vehicles in its road segment, and stores the corresponding virtual distance information. On the contrary, if a vehicle is placed at an intersection zone, it processes the connectivity fields received from vehicles placed at all the adjacent road segments. By storing the virtual distance information contained in the received *CFs*, it learns the multi-hop connectivity status of these road segments.

5.4 IFTIS

DiRCoD has been evaluated using the Infrastructure-Free Traffic Information System (IFTIS) [58] as a benchmark for performance comparison. Like DiRCoD, IFTIS is a fully distributed mechanism that aims at supporting vehicular routing protocols in the dynamic selection of geographical forwarding paths. Differently from DiRCoD, the information delivered by IFTIS at road intersections is the estimated vehicular density of adjacent road segments. For this reason, IFTIS has been chosen to justify the convenience of performing DiRCoD's direct multi-hop connectivity estimations instead of vehicular density assessments. In addition, IFTIS provides intelligent mechanisms to control the required communications overhead, which makes its comparison with DiRCoD interesting.

5.4.1 IFTIS operation

IFTIS also considers a road network representation consisting of a set of road segments and intersections. However, differently from DiRCoD, IFTIS considers that road segments are divided into equally distributed cells of radius equal to the vehicles' communications range. Let us consider the road segment depicted in Figure 5-7.

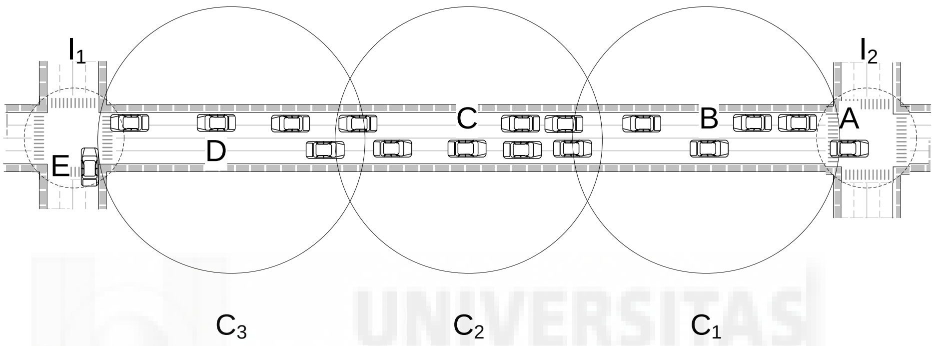


Figure 5-7. IFTIS' road segment representation.

An assessment of the road vehicular density is required at intersection I_1 to drive possible routing decisions. To perform this assessment, IFTIS uses dedicated GeoNetworking messages called "*Cell Density Packets*" (*CDPs*). A *CDP* is generated by vehicles driving in the direction $I_1 \rightarrow I_2$ upon arriving at intersection I_2 (like vehicle A in Figure 5-7). The *CDP* has intersection I_1 as final destination but is multi-hop transmitted in such a way to subsequently address the center of each road cell. For each of the cells along the road segment, the *CDP* uses a greedy forwarding method addressing the closest vehicle to the cell center. In Figure 5-7, the addressed vehicles are vehicle B, C and D for cells C_1, C_2 and C_3, respectively. The adopted *CDP* forwarding method is a sender-based mechanism. By recalling the definitions of Section 3.2.2, this means that a *CDP* forwarder selects the next hop as the closest neighbour to the next targeted cell center. Upon receiving a *CDP*, a vehicle consults its location table to assess whether it is the closest vehicle to the addressed cell center. If it is the case, then it performs a cell density estimation. To do so, it counts the number of neighbours stored in the location table whose position is inside the cell. With this value, the vehicle updates a cell-specific field of the *CPD*, and forwards the packet towards the next cell. In this way, the *CDP* is subsequently updated with the vehicular density of the cells along the road segment. After reaching the last cell of the road segment (cell C_3 in Figure 5-7), the *CDP* is addressed towards the closest vehicle to the center of I_1 (vehicle E in Figure 5-7). Upon receiving the *CDP*, this vehicle broadcasts this packet. In this way, vehicles entering I_1 from any direction get an estimation of the vehicular density of the road segment. With this estimation, these vehicles can evaluate the convenience of forwarding packets in this direction.

An interesting feature of IFTIS is its capability to address scalability issues. IFTIS considers that only vehicles that previously updated a *CDP* at one of the cell centers will generate a new *CDP* when arriving at I_2. In this way, the generation of *CDPs* and the consequent rate of road density estimations, get naturally adapted to how the road traffic flow towards I_2 is smooth. Higher vehicular densities generally result in less dynamic traffic flows. In these conditions, the vehicular density does not change rapidly, therefore there is no need to perform road density estimations very frequently. With high vehicular density, vehicles arrive at I_2 with reduced frequency, and hence the *CPD* generation rate is also reduced. As a result, IFTIS is scalable since it generates less communications overhead in conditions of higher presence of vehicles.

5.4.2 Cell density packet structure and processing

IFTIS' *CDPs* can be implemented to be fully compliant with the format defined by ETSI for GeoNetworking transmissions (Section 2.5.2). A standard GeoBroadcast packet can be adopted to carry the geographical coordinates of the intersection in which the *CDP* has to be broadcasted after traversing the road segment's cells. However, the GeoBroadcast format would need extensions to carry the information required to forward the *CDP* through the road cells as described in the previous section. Fields to store the vehicular density of road cells should be also added. These extensions correspond to the *CDP* structure as reported by [58], and represented in Figure 5-8. As it can be seen, the *CDP* consists of a first portion of fixed size including information about the road segment identifier (Road Segment ID), and the packet's Generation Timestamp. After this portion, the *CDP* includes information about each cell of the road segment. As a result, the size of this second portion is proportional to the number of cells the road segment is divided into. As defined in the previous section, the radius of a road cell is equal to the adopted communications range. As a result, the number of *CDP* fields dedicated to road cells depends on the communications range and on the road segment's length. The part of the *CDP* dedicated to each cell consists of three subfields: the cell identifier (Cell ID), the Cell Position, coded as the geographical coordinates of the cell center, and t*he Cell Density.*

Apart from the Cell Densities, all the fields indicated in Figure 5-8 are initialized by the vehicle that generates a *CDP* (vehicle A in Figure 5-7). The Cell Position fields are used to iteratively forward the *CDP* to the closest vehicles to cell centers. When finally broadcasted in the destination intersection (I_1 in Figure 5-7), receiving vehicles analyze the Road Segment ID field to understand to what road segment the *CDP* is referred to. By processing the information contained in the various Cell Density fields, vehicles can retrieve the overall density of the road segment and store this value along with the value contained in the Generation Timestamp field.

ROAD SEGMENT ID	GENERATION TIMESTAMP

CELL 1 ID	CELL 1 POSITION	CELL 1 DENSITY
CELL 2 ID	CELL 2 POSITION	CELL 2 DENSITY
CELL 3 ID	CELL 3 POSITION	CELL 3 DENSITY
•	•	•
CELL n ID	CELL n POSITION	CELL n DENSITY

Figure 5-8. IFTIS' *CDP* format.

5.5 Performance evaluation

This section describes the performance of DiRCoD in terms of capability to provide reliable and up-to-date multi-hop road connectivity estimates, and to ensure an efficient use of the communications channel. DIRCoD's evaluation has been performed using IFTIS as a benchmark. Before analysing the simulation results, this section outlines the scenario adopted for the evaluations, and defines the metrics that have been used for performance comparison.

5.5.1 Simulation scenario

The performance results described in this chapter have been obtained through simulations over the ns-3 testbed described in Section 4.4. DiRCoD and IFTIS are mechanisms aimed at supporting the operation of vehicular routing protocols. Similarly to other standard GeoNetworking functionalities like the Beaconing Protocol and the Location Table [33], they can be included in the Transport & Network layer of the ETSI ITSC Architecture (Section 2.5.2). In Section 4.4.4, it has been explained that ns-3 is the iTETRIS block emulating the ITSC Transport & Network layer. To simulate the operation of DiRCoD and IFTIS, ns-3 does not require interactions to the rest of the iTETRIS blocks. For these reasons, the implementation and simulation of DiRCoD and

IFTIS can be limited to ns-3. ns-3 retrieves vehicles' position updates by reading realistic SUMO vehicular traces. It is important to briefly recall that the iTETRIS version of ns-3 has extended the default version in order to enable realistic and standard-compliant simulations of vehicular communication protocols. In iTETRIS, ns-3 reproduces all the communications-related layers of the ETSI ITSC stack. In addition, it carefully models the radio propagation effects of pathloss, shadowing and multipath fading under LOS and NLOS conditions. The probabilistic nature resulting from radio transmission effects is taken into account through the inclusion of the PER (Packet Error Rate) performance as a function of the Signal to Interference and Noise Ratio (SINR).

The performed simulations emulate the operation of IFTIS and DiRCoD on a single road segment. This segment is similar to those shown in Figure 5-2 and Figure 5-7, and is included in a wider Manhattan-like road network consisting of roads that cross each other perpendicularly. No traffic lights are present at road intersections. Vehicles on perpendicular road segments are under NLOS conditions. It is important to remark that a Manhattan-like road network is adopted only to ease the implementation of the protocols. As mentioned in Section 5.2.2, the operation and performance of DiRCoD are expected to be maintained in other types of road networks, as long as they can be represented as sets of road segments divided by anchor points. The road segment over which DiRCoD and IFTIS are tested has a length of 500m, one lane per direction, and is delimited by two intersection zones with a radius R of 30m. Vehicular traces are generated by SUMO in order to reproduce three different average vehicular densities that are used to evaluate their impact on the protocols' performance. In the considered road network scenario, a vehicular density of 8 vehicles/km/lane results in light traffic. In these conditions, queues of vehicles at intersections are sporadic and in no case longer than a few vehicles. With a density of 10 vehicles/km/lane, the traffic gets moderate. In fact, queues start to appear with higher frequency and contain more vehicles. Finally, with a density of 12 vehicles/km/lane queues are always present.

Vehicles communicate using 5.9GHz ETSI ITS G5A radio interfaces, and transmit on the control channel (G5CC) at a 6Mbit/s data rate following the 1/2 QPSK scheme of the standard [10] (See Table 2-2). Every simulated vehicle broadcasts beacon messages with a 2Hz frequency. Different transmission powers (14, 17, 20 and 23dBm) are considered in order to investigate how they influence the performance and operation of the compared mechanisms. Varying the transmission power influences DiRCoD's and IFTIS' design parameters. In fact, DIRCoD's road section length and IFTIS' cell radius are defined to be equal to the vehicles' communications range. As explained in Section 5.2.2, this work defines the communications range as the LOS inter-vehicle distance at which 99% of the transmitted beacons are successfully received at a given transmission power. The DiRCoD's parameter p_{max}, defined in Section 5.3.1 as the maximum distance at which a vehicles receive beacons, also depends on the used transmission power. In this context, Table 5-1 reports the values of the communications range and parameter p_{max}, for each of the simulated transmission powers. These values have been retrieved through simulations. The results of these simulations are shown in Figure 5-9. The figure depicts the probability to correctly receive beacon messages as a function of the LOS inter-vehicular distance and adopted transmission power. The adopted propagation model is the WINNER B1 model [147] described in Section 4.4.5.3.

Transmission Power [dBm]	**Communications Range [m]**	p_{max} **[m]**
14	60	380
17	75	400
20	95	430
23	115	480

Table 5-1. DiRCoD and IFTIS parameters as a function of the transmission power.

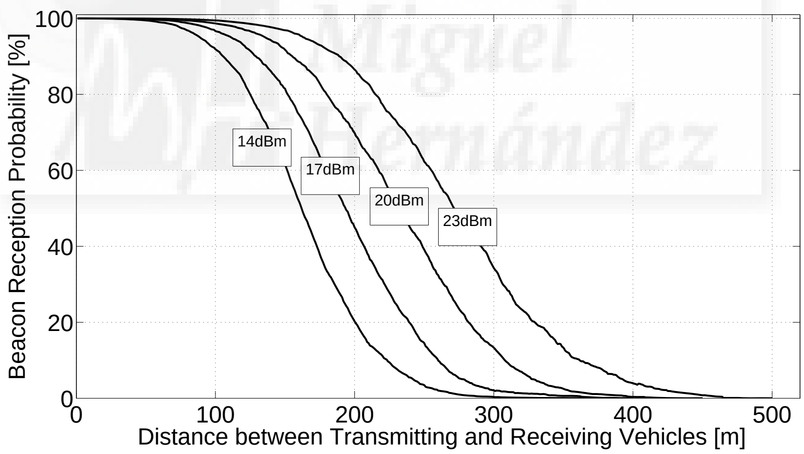


Figure 5-9. Beacon reception probability as a function of the distance between transmitting and receiving vehicles for different transmission powers.

The parameter T_{max}, defined in Section 5.3.1 as the maximum duration of the DiRCoD timer T_1, has been set to 0.1s. The duration of the timer T_2, defined in Section 5.3.1 as the *CF generation period*, has been varied in the range [1-3s] in order to assess its impact on the performance of DiRCoD.

It is important to highlight that in order to avoid that IFTIS' *CDPs* are transmitted over unreliable links, a mechanism for reliable *CDP* forwarders' selection has been implemented. In the selection of *CDP* forwarders, IFTIS only considers reliable neighbours according to the DiRCoD's neighbour reliability definition given in Section 5.3.3. This mechanism was not presented in the original IFTIS proposal [58]. Its adoption was necessary after noticing IFTIS' poor performance under realistic radio propagation models.

DiRCoD's and IFTIS' simulated packets fully comply with the format defined by ETSI for GeoNetworking transmissions (Section 2.5.2). As explained in Section 5.3.5, DiRCoD codes the *CF* with 1 byte and includes it over standard beacon messages if necessary. IFTIS' *CDP* packets are implemented as GeoBroadcast packets extended to carry the information about each road cells' vehicular density. For the *CDP* portion dedicated to an IFTIS cell (see Figure 5-8), 9 bytes have been considered: 8 bytes are used to code the coordinates of the cell's center (Cell Position field), and 1 byte is used to represent the cell density (Cell Density field). The coordinates of the cell centers are coded using 8 bytes following ETSI GeoNetworking definitions [33]. According to these definitions, every geographical position is coded with 4 bytes for the latitude and 4 bytes for the longitude. Concerning the Cell Density field, it has been considered that 1 byte is enough to represent high density scenarios consisting of up to 255 vehicles per IFTIS cell. Since the identification of an IFTIS' road cell can be automatically retrieved from its coordinates, the *Cell ID* fields of Figure 5-8 have not been included in *CDPs*. For the *CDP* portion of fixed side, 12 bytes have been used. 8 bytes are adopted for the Road Segment ID field, and 4 bytes for the Generation Timestamp field. The 8 bytes of the Road Segment ID field contain the position of the intersection where the *CDP* are generated. Considering the example of Figure 5-7, the Road Segment ID field indicates Intersection I_2. By analyzing this field, vehicles receiving a *CDP* around I_1 understand that the vehicular density estimate refers to road segment I_1-I_2 in the direction $I_1 \rightarrow I_2$.

The results reported in the following have been obtained through simulations with an accuracy equivalent to relative errors below 0.05.

5.5.2 Performance metrics

The performance comparison described in this chapter is aimed at understanding to what extent DiRCoD and IFTIS are able to provide real time connectivity estimates of a road segment, and what is the cost that they require in term of communications overhead. To conduct this evaluation, the following three performance metrics are used:

- *Connectivity information reception probability:* defined as the probability that vehicles located at I_1 (Figure 5-2 and Figure 5-7) receive at least one road connectivity estimate before leaving the intersection zone. Road connectivity estimates are received using DiRCoD's *CFs* or IFTIS' *CDPs*. This metric represents the techniques' ability to provide vehicles at intersections with road connectivity information. Receiving this information allows vehicles to decide in real time the road segments over which they should route packets.

- *Time without connectivity information:* defined as the percentage of time that a vehicle spends in the intersection zone of I_1 (Figure 5-2 and Figure 5-7) before receiving the first connectivity information (DiRCoD's *CF* or IFTIS' *CDP*). This metric represents the techniques' ability to rapidly provide vehicles at intersections with road connectivity information.

- *Connectivity information age:* defined as the time (in seconds) between the last reception of a connectivity estimate (DiRCoD's *CF* or IFTIS' *CDP*) and the moment at which a vehicle arrives at the center of I_1 (Figure 5-2 and Figure 5-7). This metric provides a measure of the "freshness" of the connectivity information delivered by the compared techniques at intersections. Connectivity information with lower age is expected to better represent the actual connectivity status of road segments.

- *Additional communications overhead:* represents the average communications overhead (in bytes) generated by DiRCoD and IFTIS over a time range of one second. It is referred to as "additional" given that it only considers the additional information transmitted for the operation of the protocols with respect to the overhead already present on the radio channel. In this case, the overhead already present on the channel is the overhead generated for the transmission of beacon messages. DiRCoD's additional communications overhead considers the additional information needed to transmit *CFs*. IFTIS' additional communications overhead considers *CDP* packets including GeoNetworking and MAC headers.

5.5.3 Performance comparison

In IFTIS, a *CDP* packet is generated only when a vehicle arrives at intersection I_2. In addition, the *CDP* is delivered at intersection I_1 only when the road is fully connected, that is only when vehicles are distributed over the road in such a way to permit uninterrupted multi-hop transmissions from intersection I_2 to intersection I_1 (Figure 5-7). On the contrary, DiRCoD's *CFs* are delivered at intersection I_1 also in situations of partial multi-hop road connectivity (Figure 5-2b). In such cases, the *CF* is generated by one of the vehicles in the inner part of the road segment (vehicle B in Figure 5-2b), irrespectively of the presence of vehicles at intersection I_2. As a result, DiRCoD's *CFs* are expected to be received at I_1 more frequently than IFTIS' *CDPs*. In order to generate fair comparisons with IFTIS, the performance of DiRCoD has been computed for two distinct configurations. In the first one, DiRCoD is analyzed in its capability to deliver *CFs* at I_1 only in situations of full multi-hop road connectivity (Figure 5-2a). This configuration is indicated by "DIRCOD F" in the next figures, with "F" indicating "Full connectivity". In the second configuration, DiRCoD is analyzed in its capability to deliver *CF* in any situation, that is under both full and partial multi-hop road connectivity conditions. In the next figures, this configuration is indicated by "DiRCoD". For all the configurations, the performance of DiRCoD has been assessed with different values of the *CF generation period*. In the next figures, "DIRCOD x" refers to a *CF generation period* of x seconds.

Figure 5-10 depicts, for a transmission power of 20dBm, the connectivity information reception probability as a function of the vehicular density. For both DiRCoD and IFTIS, this probability increases with higher values of the density. This results from the fact that higher vehicular densities benefit the creation of multi-hop connected paths over which connectivity estimates can be forwarded towards I_1. Moreover, the higher the vehicular density, the higher the time a vehicle spends at I_1, and consequently the higher the probability to receive connectivity estimates before leaving the intersection. The results of Figure 5-10 show that DiRCoD achieves a higher probability to deliver such estimates independently of the simulated vehicular density. Even if DiRCoD was used to detect only situations of full connectivity ("DIRCOD F" in the figure), its performance would yet be higher than that obtained by IFTIS. This is due to the fact that DiRCoD estimates are generated regularly as a complement of the standard beaconing protocol. An interesting feature of DiRCoD is that it can properly notify the partial multi-hop connectivity status of the road segment even in conditions of low vehicular density, where IFTIS has considerably lower performance.

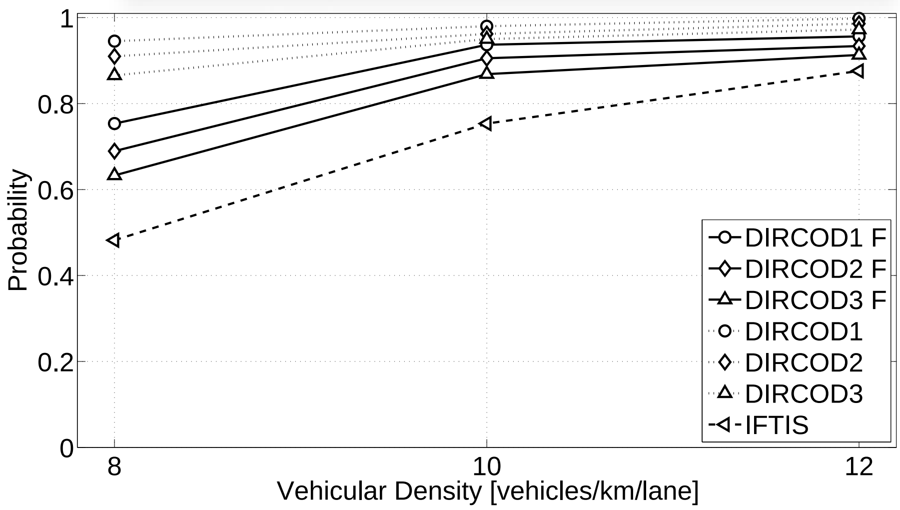


Figure 5-10. Connectivity information reception probability as a function of the vehicular density (20dBm transmission power).

As Figure 5-10 shows, DiRCoD always performs better than IFTIS even if higher values of the *CF generation period* are adopted. In this case, DiRCoD's connectivity information reception probability is only slightly degraded passing from a *CF generation period* of 1s to a value of 3s. The lower performance of IFTIS is due to the fact that *CDPs* are only generated by vehicles that previously updated the *CDPs* at road cells once they arrive at intersection I_2. As a result, *CDPs* are generated less regularly than DiRCoD's *CFs*. Moreover, since *CDPs* are generated at I_2, they necessarily need a fully connected forwarding path towards I_1 to be successfully delivered to this intersection.

The connectivity information reception probability obtained by the compared mechanisms with increasing values of the transmission power has similar trends to those depicted in Figure 5-10. Figure 5-11 shows these results for a vehicular density of 10 vehicles/km/lane. With a fixed vehicular density, increasing the transmission power augments the connectivity information reception probability as a result of a higher communications range. In turn, a higher communications range implies a higher probability to find forwarders for multi-hop connectivity information transmissions towards I_1. The obtained results show that DiRCoD is able to deliver connectivity information at I_1 with a higher probability, irrespectively of the used transmission power. Figure 5-11 confirms that using higher values of the *CF generation period* does not considerably influence this capability.

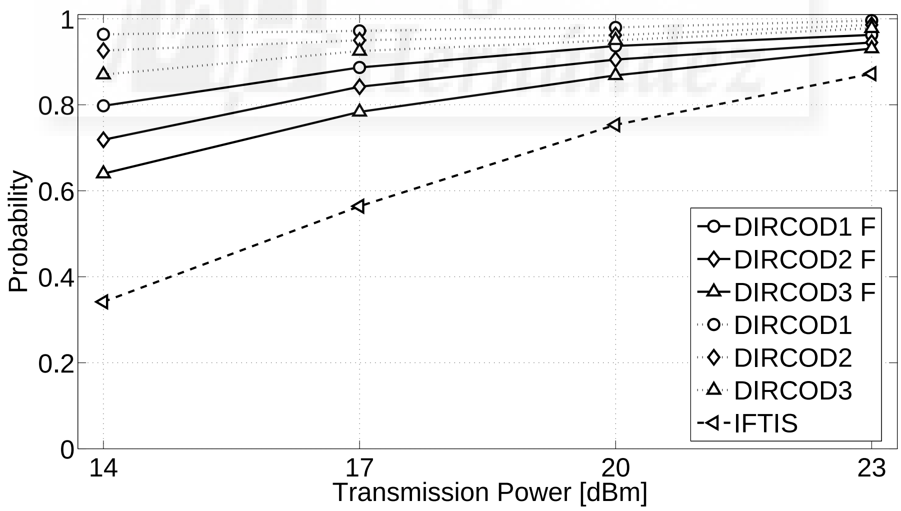


Figure 5-11. Connectivity information reception probability as a function of the transmission power (10 vehicles/km/lane vehicular density).

As previously explained, IFTIS' operation depends on traffic flow dynamics. This dependence may cause an irregular generation of *CDP* packets at I_2. This in turn may imply that *CDPs* are delivered at I_1 with variable frequency. Let us suppose that a vehicle at I_1 has to decide over which road segment to route a packet. If this vehicle bases its routing decisions on the density information contained in *CDPs*, receiving *CDPs* with irregular frequency might result in deciding with stale density information. To better investigate this aspect, Figure 5-12 represents the cumulative distribution function (CDF) of the percentage of time that a vehicle spends in the intersection zone of I_1 before receiving the first connectivity estimate (DiRCoD's *CF* or IFTIS' *CDP*). In this case, a transmission power of 23 dBm and a vehicular density of 10 vehicles/km/lane are considered (similar trends are observed for other configurations). Before receiving a connectivity estimate, a vehicle has no information to drive possible routing decisions. Therefore, it is important to keep this time as low as possible. Figure 5-12 shows that using IFTIS, 80% of vehicles already received a *CDP* when entering the intersection zone of I_1. On the other hand, with DiRCoD 80% of vehicles can spend up to 23% of their time in the intersection zone before receiving the first *CF*. IFTIS' better performance is due to the fact that a *CDP* is broadcasted upon being received by a vehicle at I_1. As a result, most of the vehicles around I_1 receive these broadcast messages before entering the intersection zone. Considering this, it is necessary to understand to what extent the connectivity information that vehicles hold when crossing I_1 is up-to-date. Up-to-date information is expected to better represent the actual connectivity status of the road segment, and support routing decisions at I_1 more effectively. In this context, Figure 5-13 shows the *CDF* of the age (in seconds) of the connectivity information that vehicles hold when getting at the center of I_1 (connectivity information age). Figure 5-13 also refers to a configuration with a transmission power of 23dBm and a vehicular density of 10 vehicles/km/lane. The depicted results show that the age of DiRCoD's *CFs* is generally much lower than that of IFTIS' *CDPs*, and in no case higher than 4s. On the contrary, the IFTIS' density information hold by vehicles at I_1 can be up to 12s old in some cases.

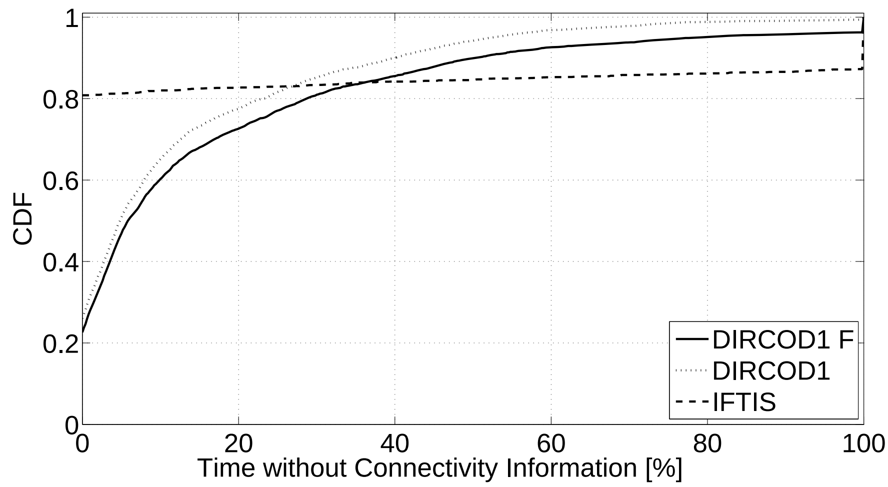


Figure 5-12. CDF of the percentage of time spent at I_1 before receiving a connectivity estimate (23dBm transmission power, 10 vehicles/km/lane vehicular density).

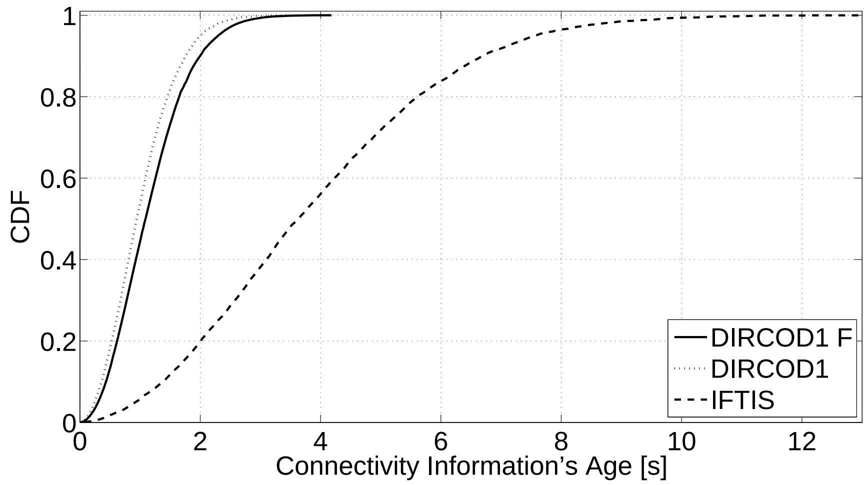


Figure 5-13. CDF of the connectivity information age at I_1 (23dBm transmission tower, 10 vehicles/km/lane vehicular density).

Besides measuring the ability to provide vehicles at intersections with up-to-date road connectivity information, it is also important to evaluate the amount of communication resources required by DiRCoD and IFTIS. In this context, Figure 5-14 and Figure 5-15 represent the additional communications overhead generated by these mechanisms and averaged over a time range of one second. In Figure 5-14, this overhead is evaluated as a function of the vehicular density, and using a transmission power of 20dBm. On the other hand, Figure 5-15 depicts how the overhead varies for increasing values of the transmission power when the vehicular density is 10 vehicles/km/lane. These figures only show the overhead required by DiRCoD to deliver *CF* in situations of full multi-hop road connectivity ("DIRCOD F"). The DiRCoD's overhead required to deliver *CF* in conditions of both full and partial road connectivity are slightly higher. These results have been omitted to ease the readability of the figures, and to show fair comparisons with IFTIS, that is only able to return vehicular density estimates when roads are fully connected. The results clearly show that DiRCoD's connectivity discovery mechanism generates a much lower (up to two orders of magnitude) communications overhead than IFTIS. To forward its *CFs*, DiRCoD just requires adding one byte information on a very limited number of standard beacon messages. On the contrary, IFTIS produces a higher overhead as it uses dedicated GeoNetworking packets to transmit its *CDPs*. As Figure 5-14 shows, increasing the vehicular density implies a higher overhead. In fact, with higher densities more vehicles are involved in the generation and forwarding of DiRCoD's *CFs* or IFTIS' *CDPs*.

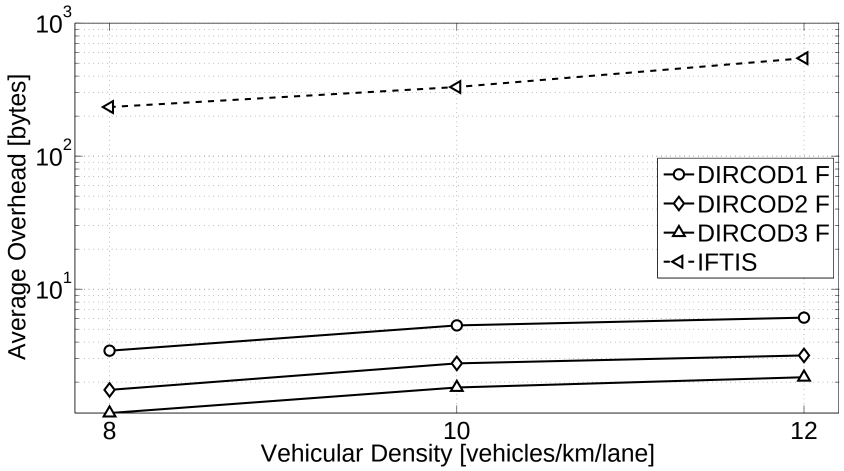


Figure 5-14. Additional communications overhead as a function of the vehicular density (20dBm transmission power).

On the contrary, Figure 5-15 shows that DiRCoD's and IFTIS' overhead stays almost constant for increasing values of the transmission range. With lower transmission powers, DiRCoD's *CFs* and IFTIS *CDPs* are transmitted through more hops of shorter length, but only a reduced part of them is successfully delivered at I_1. As a result, transmitting with lower transmission powers almost implies the same overhead as produced with higher powers, where less hops are needed, but more connectivity estimates correctly reach I_1. As both Figure 5-14 and Figure 5-15 indicate, DiRCoD's overhead can be further reduced by increasing the *CF generation period*. Very interestingly, such overhead reductions do not imply significant worsening in the probability of receiving road connectivity information at I_1 (see Figure 5-10 and Figure 5-11).

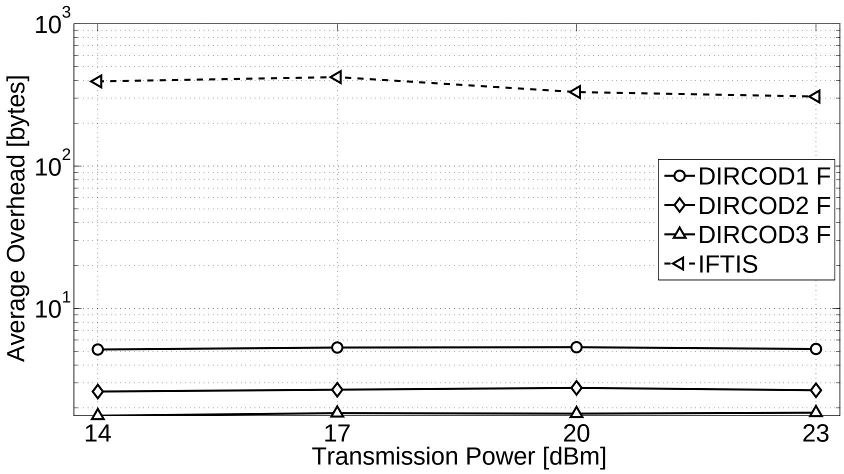


Figure 5-15. Additional communications overhead as a function of the transmission power (10 vehicles/km/lane vehicular density).

5.6 Summary and discussion

Vehicular GeoRouting protocols based on a dynamic selection of geographical forwarding paths have been shown in the literature to improve the performance of traditional schemes. For the selection of these paths, there is the need of mechanisms aimed at computing and updating the capability of road segments to support multi-hop transmissions. Most of the mechanisms presented in the literature derive this capability from vehicular density estimations. However, assessing road vehicular density in a distributed way can result in a significant communications overhead that in turn may compromise their practical viability. In addition, vehicular routing protocols that base their forwarding path selection on vehicular density may result in always choosing the densest roads, which are also the most prone to suffer channel congestion. To overcome these limitations, this chapter has presented DiRCoD, an efficient and lightweight mechanism that estimates the forwarding capabilities of road segments in terms of multi-hop connectivity. This is done in a fully distributed manner using standard beacon messages. As demonstrated throughout the chapter, DiRCoD presents intelligent design solutions that enable its practical implementation and ensure its effectiveness and efficiency. To evaluate DiRCoD's performance, an extensive set of realistic simulations has been performed. For this evaluation, DiRCoD has been compared against the IFTIS' proposal for road vehicular density estimation. As clearly shown by the obtained results, DiRCoD can dynamically and precisely assess the multi-hop connectivity capability of road segments with a very limited communications overhead. This encourages the adoption of DiRCoD for the design of advanced vehicular routing techniques based on multi-hop road connectivity awareness.

6

Contention-based Forwarding with Multi-hop Connectivity Awareness

To correctly support cooperative applications based on multi-hop transmissions, vehicular GeoRouting protocols have to detect in real time the most convenient geographical forwarding paths. These paths should contain a sufficient number of forwarders to ensure reliable end-to-end transmissions. At the same time, it is advisable that these paths do not contain road segments that are prone to suffer channel congestion. Over the selected paths, vehicular GeoRouting protocols have to choose forwarding nodes in such a way to face the challenges of vehicular communications. As described in Section 3.2, most of the recent vehicular GeoRouting proposals, select their forwarding paths based on the vehicular density of candidate road segments. In addition, these proposals generally choose forwarding nodes using sender-based forwarding schemes. However, estimating the road vehicular density in VANETs may imply generating high levels of communications overhead. In addition, sender-based forwarding schemes may result in choosing unreliable radio links compromising the end-to-end delivery performance. To solve these inefficiencies, this chapter presents TOPOCBF (Road Topology-Aware Contention-Based Forwarding), a novel vehicular routing protocol using a contention-based forwarding scheme over paths that are dynamically selected based on real time multi-hop road connectivity instead of vehicular density. Compared to traditional sender-based schemes, the TOPOCBF's contention-based approach provides reliability to packet forwarding. In addition, computing and sharing the multi-hop road connectivity generates less channel load, and permits a better spatial distribution of the communications traffic. Simulation results demonstrate that TOPOCBF ensures good packet delivery ratios, efficiently manages the communications channel, and can also reduce the spatial probability of channel congestion.

In the rest of this chapter, Section 6.1 better defines the motivations of the TOPOCBF routing approach. Section 6.2 presents a conceptual overview of TOPOCBF, while Section 6.3 explains the details of its implementation. Section 6.4 describes the GyTAR routing protocol chosen as a benchmark to compare the TOPOCBF's performance described in Section 6.5. Section 6.6 concludes this chapter with a short summary and some necessary considerations.

6.1 Motivations

Section 3.2.2 explained that vehicular GeoRouting relies on a greedy forwarding approach in which forwarding nodes are selected according to their capability to provide progress towards the final destination. However, greedy forwarding techniques may suffer the "local maximum" problem every time a packet reaches a node that has no neighbors offering such progress. This problem can be particularly relevant in urban routing scenarios, where the presence of buildings can hide the best forwarders, and generate situations of local maximum with higher frequency [47]. An example is depicted in Figure 6-1, where a packet to be routed from the source S towards the destination D is currently hold by vehicle G. The shielding effect of the buildings results in that vehicle G cannot perceive the presence of possible forwarders over the road segment I_1-I_2. Applying a simple greedy forwarding scheme in this case would result in forwarding the packet to vehicle F. Vehicle F is in fact the neighbor providing G with the highest progress towards the destination, but also a local maximum. In case of a local maximum, a protocol might either delay the forwarding by waiting for contacts with new vehicles, or drop the packet and consequently reduce the end-to-end delivery performance. To overcome these limitations, map-assisted protocols extended the greedy forwarding scheme by iteratively targeting vehicles placed at intermediate road intersections along the route towards the final destination. Transmissions from vehicles placed at road intersections exploit LOS propagation conditions towards different directions. These conditions permit a more precise selection of forwarders and the use of reliable radio links. However, map-assisted schemes need to smartly and efficiently select intermediate road intersections, which results in the problem of selecting geographical forwarding paths. In this context, studies like [51] highlighted that this selection must take into account the uneven distribution of the vehicular traffic over different streets, as it can impact the delivery performance of vehicular routing protocols.

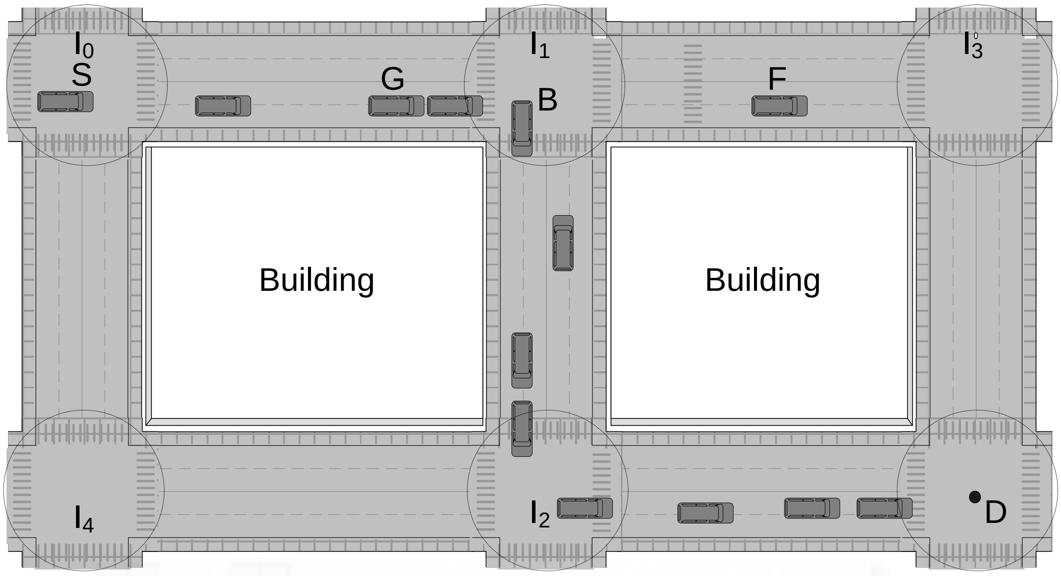


Figure 6-1. Effect of buildings on the operation of vehicular greedy forwarding protocols.

Starting from this consideration, various vehicular GeoRouting proposals select geographical forwarding paths based on the vehicular density of road segments [51][52][54][57]. Forwarding paths with a high presence of vehicles are probable to prevent that packets get blocked in local maxima, and thereby better support end-to-end multi-hop transmissions on average. The most advanced related proposals do not use forwarding paths composed by fixed sets of consecutive intersections or road segments. On the contrary, they renew the choice of geographical forwarding paths while the packet is being routed towards its destination [54][57]. This feature permits routing protocols to dynamically adapt to possible variations of vehicular traffic flows and better react against unexpected path disconnections. The geographical forwarding paths are iteratively recomputed at road intersections based on the real time vehicular density experienced by candidate road segments. Studies such as [54] and [58] demonstrated that the density of road segments can be computed by vehicles in a distributed way using vehicular communications. This information can be made available to vehicles at intersections to support their routing decisions. However, as it has been demonstrated in Chapter 5, a distributed computation of road vehicular density may require a high communications overhead. Also, using vehicular density as a metric to drive forwarding path selections may cause that packets are always routed over roads that are more prone to suffer channel congestion. As previously discussed, this effect should be carefully prevented to enable a scalable operation of VANETs.

As mentioned in Section 3.2.2, most of the proposed vehicular routing protocols consider the use of sender-based schemes for inter-vehicle packet forwarding. Following the greedy forwarding approach, in sender-based schemes a packet is unicasted to the neighbor providing the higher progress towards the targeted destination. In case adverse channel conditions impair communications and cause failures, a unicast packet can be retransmitted a limited number of times at MAC layer [29]. In this context, sender-based greedy forwarding might be expected to effectively reduce the latency and number of hops to reach the final destination. However, the greedy selection of forwarders increases the distance between consecutive hops, and hence can result in transmitting over unreliable radio links. This in turn may increase the overhead due to transmission retries [61], or require additional protocol complexity for detecting reliable links [62][63].

The greedy forwarding approach can also be operated through contention-based schemes. In contention-based forwarding schemes the routed packets are broadcasted. Receiving nodes activate contention mechanisms that, according to some local information (e.g. vehicle placement, neighbor density, etc.), determine the next forwarder in a distributed manner (for this reason, contention-based forwarding is also referred to as receiver-based forwarding). Differently from the unicast case, standard vehicular broadcast transmissions do not account for retransmissions at MAC level. Nevertheless, they permit that at least one node among the receivers will be able to correctly decode and forward the packet, which can provide robustness. Due to its broadcast nature, contention-based forwarding in VANETs has been mostly adopted for information dissemination. However, it can be also used for vehicular GeoRouting. As demonstrated in [61], in highway scenarios the CBF contention-based protocol largely overcomes the performance of a simple sender-based greedy forwarding scheme. CBF's superior performance is demonstrated in terms of both generated communications overhead and end-to-end delivery capability. In highway scenarios, the vehicular mobility is higher. In these conditions, the sender-based approach does not have adequate up-to-date information about neighbors' locations to reliably select forwarders. Even exchanging beacons with high frequency (up to 4Hz), the sender-based scheme results in packet failures and transmission retries. On the contrary, CBF achieves high delivery ratios without requiring transmission retries and frequent beaconing.

At the time of performing this study, only a limited number of works applied contention-based forwarding to vehicular routing in urban scenarios. The authors of [47] analyzed CBF in such scenarios using realistic propagation models capable to reproduce the shielding effect of buildings. In these conditions, CBF can unintentionally replicate packets over different streets. This effect increases the chances to find a multi-hop connected route to the final destination, but might also flood the network with redundant overhead. The CLA-S contention-based proposal [65] introduced the concept of "forwarding area". The forwarding area is defined a set of parallel streets and intersections around the line that ideally connects source and destination nodes. Over this area, CLA-S intentionally replicates the routed packets in order to create parallel forwarding paths providing robustness to end-to-end multi-hop transmissions. However, these replications might overload the channel, especially over roads characterized by high presence of vehicles. To solve this issue, the CBRP protocol [64] uses the contention-based scheme to iteratively address subsequent "static nodes" placed at intersections. These static nodes inform vehicles about real time traffic conditions over different road segments. Thank to this information, packets can be forwarded over a single geographical forwarding path that is dynamically updated according to the roads' capability to support multi-hop transmissions. However, CBRP would result effective only if static nodes were fully deployed over the road network, which is highly unrealistic. Contrary to CBRP, the BRAVE [66] contention-based GeoRouting proposal does not use static nodes. It computes the geographical forwarding path as the shortest path to the destination by using the Dijkstra algorithm. For this computation, no real time estimation of the actual forwarding capability of roads is considered.

In this context, this chapter presents a novel vehicular routing approach called Road Topology-Aware Contention-Based Forwarding (TOPOCBF). TOPOCBF exploits the benefits and overcomes the limitations of the previously proposed schemes. Like the most advanced routing proposals, TOPOCBF dynamically renews the selection of its geographical forwarding paths at intersections. In this way, it is able to exploit the real time connectivity conditions of candidate road segments. Over these paths, TOPOCBF uses broadcast transmissions and selects consecutive forwarders with a reliable contention-based approach. As detailed in the following, TOPOCBF forwarding path selection is driven by a real time analysis of DiRCoD multi-hop road connectivity estimates. The previous chapter proved that estimating the multi-hop road connectivity is feasible with much less communications overhead than assessing the road vehicular density. The following of this chapter demonstrates that selecting the forwarding path with the DiRCoD multi-hop road connectivity metric allows TOPOCBF not to always route packets over the roads that can suffer channel congestion. In addition, the use of the DiRCoD metric prevents TOPOCBF's contention-based approach to be replicated over parallel forwarding paths. Compared to schemes like CBF and CLA-S, this features can reduce the communications overhead. TOPOCBF presents design solutions ensuring an efficient application of the contention-based forwarding mechanism in scenarios consisting of roads and intersections. These solutions on the one hand prevent that the uncontrolled nature of broadcast transmissions result in flooding the network redundant with packet replicas. On the other hand, they avoid that unnecessary delays are cumulated in the distributed computation of forwarding nodes.

6.2 TOPOCBF concept

This section briefly outlines the definitions and the operational principles of the TOPOCBF protocol. It also introduces the CBF contention-based protocol that has been selected as the basis for the implementation of TOPOCBF.

6.2.1 Definitions and principles

To explain TOPOCBF's principles and operational details, this chapter considers the same road network representation and nomenclature as introduced in Section 5.2.1. The routing scenario is represented as a set of road segments delimited by intersections. Circular intersection zones of radius *R* are centered at intersections.

TOPOCBF does not route packets over fixed geographical forwarding paths composed by a given set of road segments and intersections. On the contrary, it iteratively selects, at subsequent road intersections, the road segments ensuring good capability to support multi-hop transmissions. This capability is estimated in terms of DiRCoD multi-hop connectivity. Let us consider the example illustrated in Figure 6-2 where S denotes the source and D the final destination of packets.

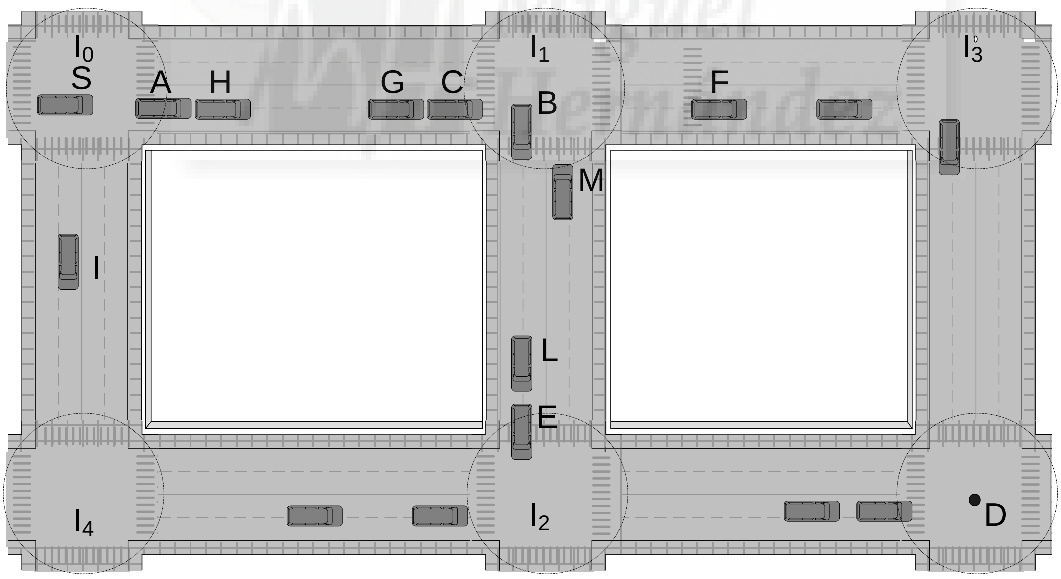


Figure 6-2. Example of vehicular routing scenario.

When vehicle B receives a packet at intersection I_1, it has to select the next anchor point (or intersection) towards which the packet has to be addressed to reach the final destination. In TOPOCBF, this selection is made within the circular intersection zones by considering two factors. The first is the DiRCoD multi-hop connectivity of the candidate road segments $I_1 \rightarrow I_2$ and $I_1 \rightarrow I_3$. Vehicle B holds estimated values of this connectivity by overhearing DiRCoD's *CFs* at intersection I_1. The second factor is the capability of the candidate target intersection I_2 and I_3 to provide progress towards the destination D. This process of selecting subsequent target intersections is repeated by TOPOCBF until the packet reaches the final destination D. Once a target intersection is selected, TOPOCBF uses a greedy forwarding scheme to reach the closest vehicle to the center of this intersection. Thanks to LOS visibility conditions, such vehicle achieves a better knowledge of the DiRCoD multi-hop connectivity status of adjacent road segments. As a consequence, it can select the next anchor point more efficiently. To forward packets towards vehicles at road intersections, TOPOCBF operates a contention-based scheme. This scheme inherits its structure from the CBF protocol that is next presented.

6.2.2 CBF protocol

The Contention-based Forwarding (CBF) protocol is a GeoRouting scheme initially designed for generic MANETs [45]. Its main objective is to overcome the limitations of sender-based greedy forwarding schemes in conditions of high mobility. In these conditions, nodes cannot have a precise knowledge of neighbours' locations at every moment. As a result, a greedy selection of forwarders can result in transmission failures, even when nodes broadcast their locations with beacon messages at a high frequency [45]. CBF proposes a mechanism to perform GeoRouting without the help of beacons messages. This is accomplished through a distributed contention process based on the actual positions of nodes. CBF uses broadcast transmissions to forward packets towards a final destination D. Every packet carries the geographical position of its sender S, and the position of its destination D. Upon receiving a packet, nodes activate a timer called "forwarding timeout". The expiration of this timer triggers the packet forwarding. At a generic node X, the duration t_X (in seconds) of the forwarding timeout is calculated by the following formula:

$$t_X = t_{\max}\left(1 - \frac{p_X}{p_{\max}}\right) \tag{6-1}$$

where p_X represents the progress that node X can provide towards the destination D. This progress is computed as:

$$p_X = d_{S-D} - d_{X-D} \tag{6-2}$$

being $d_{S\text{-}D}$ and $d_{X\text{-}D}$ the distances (in meters) separating vehicles S and X from the destination D, respectively. In equation (6-1), p_{max} (in meters) is equal to the maximum distance at which a vehicle is expected to receive a packet from the sender S, and therefore corresponds to the maximum possible progress. t_{max} (in seconds) is the maximum duration of the forwarding timeout allowed by the protocol. Using a forwarding timeout computed as in equation (6-1) results in that the closest node to the destination D is the first to forward the packet. By overhearing this transmission, the other nodes with the timeout active abort their forwarding attempt. Since a node might receive the same packet several times, a mechanism is needed not to forward this packet every time. In CBF, packets are labelled with unique identifiers (IDs). This permits recognizing packets that have been previously received. Such packets are considered duplicates, and are not further forwarded.

CBF was shown to improve the delivery performance and reduce the communications overhead compared to sender-based forwarding schemes in vehicular scenarios [61]. As it was pointed out, sender-based schemes may transmit over unreliable links, and hence require several transmission attempts to overcome packet failures. For its higher performance and design simplicity, CBF was selected as the basis for the TOPOCBF routing protocol implementation.

6.3 TOPOCBF implementation

From an operational point of view, TOPOCBF can be seen as an evolution of CBF applying the broadcast contention-based forwarding over road segments that are dynamically selected based their DiRCoD real time multi-hop road connectivity. The following of this section describes the practical solutions that make this approach possible, and the improvements that provide TOPOCBF with effectiveness and efficiency.

6.3.1 TOPOCBF packet structure

Like CBF, TOPOCBF considers that routed packets contain the position of the sender node, as well as the position of the final destination. As described in Section 2.5.2, this information is contained by default in the header of standard GeoNetworking packets used for GeoUnicat transmissions. Over a road segment, TOPOCBF uses a contention-based greedy forwarding approach to address the closest vehicle to the next targeted intersection. To address this vehicle, the geographical coordinates of the next targeted intersection are also included in the packet. These coordinates are added to the standard

GeoNetworking header, and contained in an additional field called "*Next Intersection Field" (NIF).* The resulting format of a TOPOCBF packet is depicted in Figure 6-3.

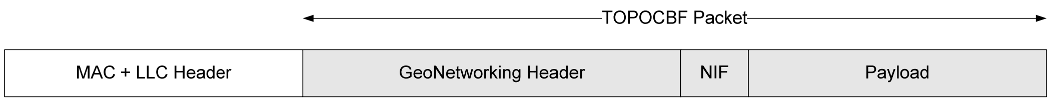


Figure 6-3. TOPOCBF packet structure.

Let us suppose that vehicle B in Figure 6-2 selects intersection I_2 as the next intersection to target. Before forwarding the TOPOCBF packet towards this intersection, the vehicle updates the *NIF* by replacing the old coordinates with those of intersection I_2.

6.3.2 Selection of target intersections

To illustrate TOPOCBF's dynamic selection of target intersections, let us still consider the scenario depicted in Figure 6-2. Vehicle B at intersection I_1 has to select the next road segment over which to route a packet towards the final destination D. Among the candidate target intersections, TOPOCBF selects the most appropriate one by sequentially analyzing the following properties:

- *Property 1: Progress towards the final destination.* Only intersections providing progress towards D with respect to the current intersection are considered. For example, in Figure 6-2 only intersections I_2 and I_3 are considered.
- *Property 2: Freshness of the road connectivity information.* Vehicle B continuously processes the received beacons to retrieve the connectivity status of adjacent road segments contained in DiRCoD's connectivity fields (*CFs*). It then checks the time at which the last *CF* referring to the intersections holding *property 1* were overheard. In the case of Figure 6-2, vehicles B is only interested in knowing the connectivity status of the road segments leading to intersections I_2 and I_3. As a results, it only checks the time at which the last connectivity fields referring to these directions (CF_{12} and CF_{13}) were received. If a received *CF* is older than a threshold referred to as "*Connectivity Expiry Time*" (*CET*), B considers that the road segment leading to the intersection under evaluation does not guarantee an adequate multi-hop connectivity. As explained in Section 5.3.2, if a road segment $I_i \rightarrow I_j$ is fully or partially multi-hop connected, a vehicle placed at intersection I_i overhears a CF_{ij} at least every *CF generation period* seconds. The absence of CF_{ij} receptions for longer periods than *CF generation period* might imply that the road segment $I_i \rightarrow I_j$ does not currently offer either full or partial connectivity. As a result, vehicle B considers as viable target

intersections only those for which the last *CF* has been received within the last *CET* seconds (with *CET* ≥ *CF generation period*).

If none of the candidate intersections satisfies *properties 1* and *2*, the routed packet is dropped. Otherwise, one further property might be considered:

- *Property 3: Road connectivity status*. If more than one candidate intersection satisfies *properties 1* and *2*, vehicle B selects the next target intersection as the one characterized by the lowest DiRCoD's virtual distance. As explained in Section 5.2.2, DiRCoD's virtual distance is contained in the overheard *CFs* and provides an indication of the multi-hop connectivity of road segments in a specific direction. The lower this quantity, the closer a packet can be forwarded to a target intersection through multi-hop transmissions.

Finally, if two or more candidate road intersections are characterized by the same lowest virtual distance, vehicle B selects one of them randomly. A flow diagram summarizing TOPOCBF's selection of target intersections is depicted in Figure 6-4.

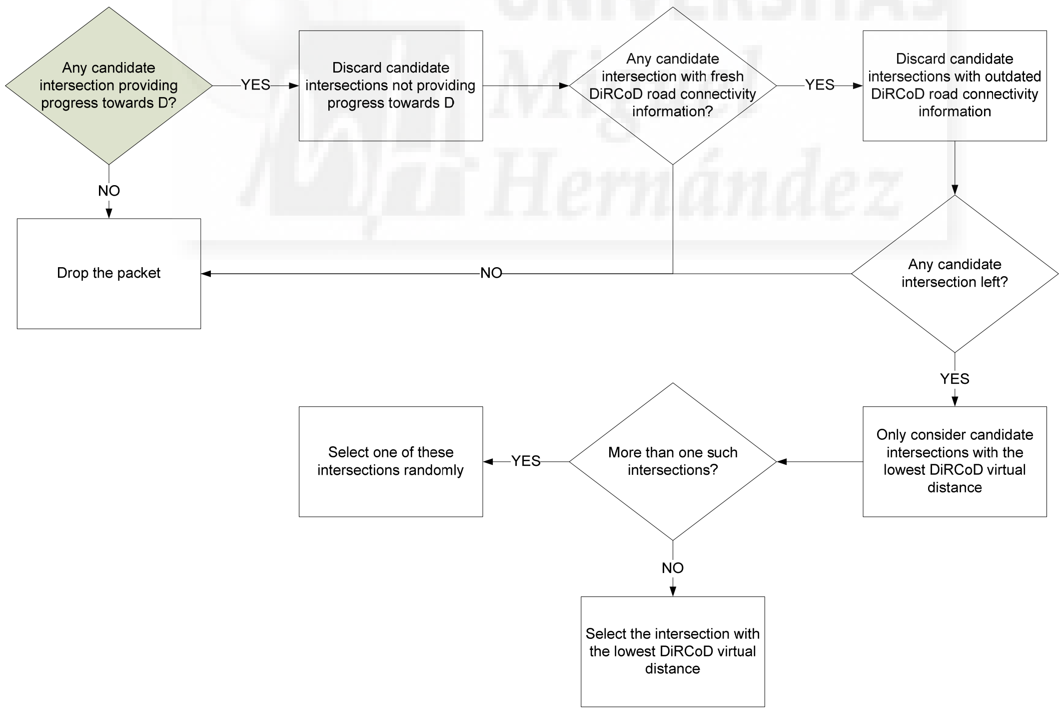


Figure 6-4. Flow diagram used for the TOPOCBF selection of target intersections.

6.3.3 Road topology-aware contention-based forwarding

Still considering the scenario depicted in Figure 6-2, this section describes how TOPOCBF applies the broadcast contention-based selection of subsequent hops over an urban road topology. Let us consider that following the properties listed in the previous section, vehicle B has selected intersection I_2 as next target intersection. As explained in Section 6.3.1, vehicle B includes the geographical coordinates of I_2 in the *NIF* of the TOPOCBF packet before broadcasting it. Among the vehicles receiving this packet, only those providing progress towards the targeted intersection I_2 activate a forwarding timeout. Let us suppose that vehicle E receives the broadcasted packet. As represented in Figure 6-5 (an enlargement of Figure 6-2), TOPOCBF's forwarding timeout t_E (in seconds) on vehicle E is computed based on the progress p_E (in meters) that this vehicle provides towards the target intersection I_2:

$$t_E = \begin{cases} t_{\max}\left(1 - \dfrac{p_E}{p_{\max}}\right) & if \quad d_{B-I2} > p_{\max} \\ t_{\max}\left(1 - \dfrac{p_E}{d_{B-I2}}\right) & otherwise \end{cases} \tag{6-3}$$

where p_{max} (in meters) is equal to the maximum distance at which a vehicle is expected to receive packets from vehicle B, t_{max} (in seconds) is the maximum forwarding timeout duration defined by the protocol, and the progress p_E is computed in this case as:

$$p_E = d_{B-I2} - d_{E-I2} \tag{6-4}$$

being d_{B-I2} and d_{E-I2} the distances (in meters) separating vehicles B and E from intersection I_2, respectively. If vehicle E detects that d_{B-I2} is higher than p_{max}, the computed forwarding timeout t_E is equal to the one that would be employed by the CBF protocol. If this is not the case, the maximum progress that vehicle E can provide towards the next intersection I_2 is bounded to the distance d_{B-I2}. To better understand the differences between TOPOCBF and CBF, the functions adopted for the computation of their forwarding timeouts are graphically represented in Figure 6-5. TOPOCBF computes the forwarding timeout considering the maximum progress a node can provide towards the next target intersection, instead of towards the final destination. As a result, its forwarding timeout on vehicle E can be Δt_E seconds shorter than that computed by CBF. This feature can reduce the end-to-end delivery latency of TOPOCBF packets compared to CBF. This effect is expected to be more evident in urban scenarios. In these scenarios, packets are generally forwarded through vehicles placed at intersections to exploit LOS propagation conditions. Letting these vehicles implement shorter forwarding timeouts prevents cumulating unnecessary delays.

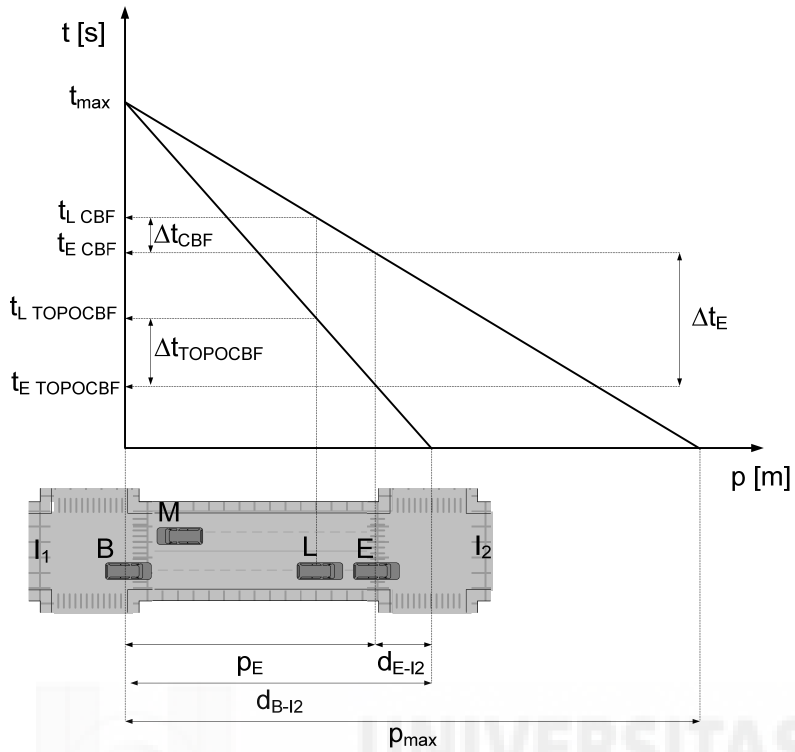


Figure 6-5. TOPOCBF and CBF forwarding timeout.

The fact that TOPOCBF forwards packets towards intermediate target intersections requires a different policy to discard packet duplicates compared to CBF. Let us consider the scenario of Figure 6-2. A packet forwarded by vehicle S and addressed to intersection I_1 is received by vehicle M. Vehicle M is placed on a road segment beyond the current target intersection. Since vehicle M is not the closest vehicle to the target intersection, it would not initially forward the packet. Based on TOPOCBF's operation, the packet is broadcasted by vehicle B, which is very close to the center of I_1's intersection zone, and sees its forwarding timeout expiring first. With this transmission, vehicle M may receive the same packet it previously received from vehicle S. If the CBF's policy was applied, vehicle M would check the packet's ID and consider it as a duplicate. As a result, the packet would be discarded. However, after vehicle B's transmission the packet is addressed towards intersection I_2. Since vehicle M provides progress towards this intersection, the second packet reception at vehicle M should not be discarded. In fact, vehicle M is a candidate to forward the packet towards I_2. To prevent such occurrences, in TOPOCBF vehicles keep track not only of the ID of received packets, but also of the value contained in their *NIF*. A packet duplicate is discarded only if a packet carrying the same ID and *NIF* has been previously received.

6.3.4 Robustness against radio propagation effects

The operation of contention-based forwarding schemes would be perfect under idealistic assumptions on the behavior of wireless transmissions. If the communications range of every node was fixed and packet collisions did not occur, every broadcast transmission would suppress the forwarding timeout at almost all the nodes competing to forward the same packet. However, wireless transmissions are influenced by radio propagation effects. The presence of large-sized obstacles (e.g. buildings) causes strong radio signal attenuations that highly impair communications between nodes under NLOS conditions. Moreover, phenomena like shadowing and multipath fading add to the received signal a given degree of variability causing receptions at longer distances and packet failures at shorter ones. All these effects have been shown to strongly influence the operation and performance of the CBF protocol [47]. To illustrate some of these effects, and show how TOPOCBF can better address their negative impact, let us consider the scenario illustrated in Figure 6-2. Let us consider that vehicles A, H and B receive from vehicle S a packet to be routed to the final destination D (and having I_1 as the next targeted intersection in the case of TOPOCBF). When vehicle B forwards the packet first, the radio signal variability might result in that one of the vehicles A or H does not overhear it. The missed suppression of the forwarding timeout on one of these vehicles generates an unwanted packet duplicate. In the unfortunate case that both vehicles A and H do not overhear the packet transmission, both these vehicles keep the forwarding timeout active. If these vehicles are very close to each other, their forwarding timeouts will have almost the same duration. As explained in [45], when the difference between the forwarding timeouts of two nodes is lower than a minimum time needed for suppression, then the nodes deliver the packet to their MAC layer at almost the same time. As a result, both these nodes transmit redundant packet duplicates. As previously explained, TOPOCBF computes the forwarding timeout with respect to the next target intersection rather than the final destination. This increases the probability of having wider differences between the timeouts of competing forwarders compared to CBF ($\Delta t_{TOPOCBF} > \Delta t_{CBF}$ in Figure 6-5). As a consequence, the design of TOPOCBF can help reducing the occurrence of multiple packet duplicates.

As shown in [47], packet duplicates can also occur at urban intersections due to the presence of buildings blocking the radio signals. To illustrate this effect, let us consider in Figure 6-2 that vehicles G and I receive from vehicle S a packet to be routed towards the final destination D. Let us suppose that the CBF protocol is used. Since vehicle G provides a higher progress towards the destination, it would forward the packet first. However, the presence of a building between the two vehicles might prevent vehicle I from overhearing vehicle G's transmission. This would result in that vehicle I also forward the packet. As a result, it unintentionally creates a parallel forwarding path towards the final destination. Parallel forwarding paths might unnecessary produce additional overhead throughout the road network. In this context, the design of TOPOCBF naturally helps reducing packet duplicates at road intersections. In the previous example, the transmission of a TOPOCBF packet from vehicle S would need to specify the next target intersection. If such intersection was I_1, vehicle I would discard the packet upon detecting that it does not provide progress towards the targeted anchor point. Only vehicle G would forward this packet.

6.3.5 eTOPOCBF variant for improved channel efficiency

The previous section has shown the capability of TOPOCBF to control and limit the redundant overhead that may be generated by the broadcast nature of contention-based forwarding schemes. However, packet duplications at intersections cannot be completely avoided by TOPOCBF. Referring again to the scenario illustrated in Figure 6-2, let us consider that a packet with I_1 as the next target intersection is originated by node S. Node S introduces the coordinates of I_1 in the *NIF* of the packet and broadcasts it. Let us suppose that this packet is received by vehicles A, H, B and G, but not by vehicle C. Being the closest node to the center of I_1, vehicle B forwards the packet first. Before forwarding, vehicle B selects I_2 as the new target intersection, and accordingly replaces the value contained in the *NIF* with the coordinates of this intersection. Let us now suppose that vehicle B's transmission is overheard by vehicle E and by all the vehicles placed in the road segment I_0-I_1, except vehicle A. The packet reception at vehicle E ensures that the packet is forwarded towards the final destination D. The reception at vehicles placed along the road segment I_0-I_1 ensures that their forwarding attempt is aborted. However, since vehicle A does not overhear vehicle's B transmission, it also forwards the packet. This packet duplicate has still I_1 as next targeted intersection. According to TOPOCBF policy described in Section 6.3.3, this duplicate is discarded by every node that has previously received the packet with a *NIF* equal to I_1. However, the packet is not discarded by vehicle C since it only received the packet from vehicle B, which modified the value in the *NIF* to include the coordinates of intersection I_2. Consequently, vehicle C has to forward the packet received from vehicle A. Being placed at a road intersection, it has also to select a next intersection to target. In this context, a parallel forwarding path can be created if vehicle C does not select the same target intersection as vehicle B, i.e. I_2.

Situations like the above-described could be more frequent in high vehicular density scenarios. In such scenarios, vehicles are separated by very short distances and often concentrate at road intersections. Moreover, with high vehicular density radio communications are further impaired by packet collisions that increase the number of packet losses. All these effects increase the probability of TOPOCBF to generate redundant packet duplications and parallel forwarding paths. It is important to remark that in such high density scenarios, the road segments composing the road network topology may all provide full multi-hop connectivity. In these conditions, parallel forwarding paths would only generate additional communications overhead without increasing the end-to-end delivery performance of contention-based schemes. To cope with this inefficiency, an improvement of the TOPOCBF scheme has been designed. eTOPOCBF (efficient TOPOCBF) selects the next target intersection like TOPOCBF, but introduces the use of two intersection fields in its packets, and changes the policy to discard packet duplicates. The first intersection field carries the position of the current targeted intersection ("*Next Intersection Field"* or *NIF*), while the second one includes the position of the previous targeted intersection ("*Previous Intersection Field"* or *PIF*). The modified structure of an eTOPOCBF packet with respect to a TOPOCBF packet is depicted in Figure 6-6.

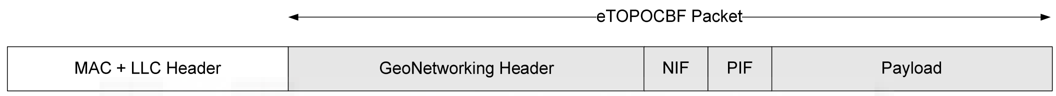


Figure 6-6. eTOPOCBF packet structure.

In eTOPOCBF, for every received packet vehicles keep track of the packet ID as well as the coordinates of the current and the previous targeted intersections. Packet duplicates are discarded by a node if it previously received a packet with the same ID, and at least one of the two intersection fields carried in the packet. To better understand this mechanism, let us reconsider the previous example. Let us suppose that vehicle C in Figure 6-2 receives the packet forwarded by vehicle B. With eTOPOCBF, vehicle C stores the value contained in the *NIF* (position of I_2, as the current targeted intersection), as well as that contained in the *PIF* (position of I_1, as the previous targeted intersection). Later on, vehicle C receives from vehicle A the packet duplicate with I_1 as the current targeted intersection (for this duplicate, the *NIF* still contains the position of I_1). However, vehicle C discards this duplicate as it detects that I_1 was a previously targeted intersection. Consequently, vehicle C does not further forward the packet at intersection I_1, which prevents the possibility to generate a parallel forwarding path and redundant communications overhead.

6.4 GyTAR description

In order to highlight the capability to route packets by dynamically selecting multi-hop connected road segments independently from their vehicular density, TOPOCBF has been compared against the improved greedy traffic-aware routing protocol (GyTAR) [57]. As previously mentioned, the aim of GyTAR is providing a vehicular routing approach to dynamically find reliable routes in urban environments. GyTAR's forwarding paths are updated at intersections while the packet is routed towards its final destination. In this context, like TOPOCBF, GyTAR aims at selecting intermediate target intersections on the way leading towards the destination. The parameters that GyTAR takes into consideration to operate this selection are the remaining distance to the final destination, and the vehicular density over candidate road segments. This vehicular density is estimated through the IFTIS protocol [58]. The packet forwarding between consecutive target intersections is performed by GyTAR adopting an improved sender-based greedy approach. This approach also takes into account a store, carry and forward mechanism to face the occurrence of temporary path disconnections. At the time of conducting this study, no other vehicular routing protocol presented in a unique solution all the interesting features provided by GyTAR. For this reason, GyTAR was selected as the benchmark to compare the performance of TOPOCBF. The rest of this section provides a more detailed description of GyTAR's characteristics and functioning.

6.4.1 GyTAR forwarding path selection

To outline the dynamic mechanism used by GyTAR to select the next target intersection, let us consider the example depicted in Figure 6-2. Every time a routed packet is received by a vehicle at an intersection (e.g. vehicle B at I_1), GyTAR selects the next anchor point as the candidate intersection I_i that provides the highest score S_i according to the formula:

$$S_i = f(P_i) + g(D_i) \qquad (6\text{-}5)$$

$f(P_i)$ returns a value that is proportional to the progress P_i offered by I_i towards the destination D. $g(D_i)$ is a non decreasing function of the vehicular density D_i offered by the road segment I_1-I_i that is estimated through the IFTIS protocol. In particular, $f(P_i)$ is calculated by the following formula:

$$f(P_i) = \alpha\left[1 - \frac{d_i}{d_1}\right] \qquad (6\text{-}6)$$

In equation (6-6), α is a protocol parameter to be optimized to weight the contribution of the term $f(P_i)$ to the overall score S_i. d_i and d_1 are respectively the distances separating I_i and I_1 from the final destination D. As it can be observed, the lower the distance d_i of a candidate intersection, the higher the progress P_i offered towards the destination with respect to the current intersection I_1. As a consequence, lower values of d_i result in higher values of the term $f(P_i)$ in equation (6-5). The term $g(D_i)$ of equation (6-5) is instead computed as:

$$g(D_i) = \beta\left[\min\left(\left(\frac{1}{1+\sigma_i}\frac{N_i}{N_{con}}\right),1\right)\right] \tag{6-7}$$

Similarly to equation (6-6), the value of β in equation (6-7) is used by the protocol to weight the term $g(D_i)$ in the computation of the score S_i. N_i and σ_i are respectively average and standard deviation values of the number of vehicles present in the cells that the IFTIS protocol decomposes the road segment I_1-I_i into (see Figure 5-7). As described in Section 5.4, vehicles running IFTIS receive at road intersections *CDP* packets carrying the number of vehicles counted in each of the road segment cells. These cell densities can then be used for the computation of N_i and σ_i. Finally, N_{con} is a protocol parameter referred to as the "ideal connectivity degree". This parameter is defined by GyTAR as the minimum number of vehicles that all the IFTIS cells should contain to ensure that a road segment can support uninterrupted multi-hop transmissions along its length. An analytical method is used in [57] to derive the optimal value of this parameter. This analysis assumes an exponential distribution of inter-vehicle distances over road segments where vehicles are assumed to communicate with a deterministic communications range. The results obtained in [57] justify always using a conservative value of 12 for the N_{con} parameter. As it can be observed, adopting equation (6-7) results in providing higher values of $g(D_i)$ to candidate road segments having higher vehicular densities that are well-balanced along the various cells. In fact, N_i / N_{con} determines to what extent the average cell density resembles the ideal connectivity degree, while $1/(\sigma_i+1)$ indicates if the density over the road segment is well balanced or not. By including the term $1/(\sigma_i+1)$ in the computation of $g(D_i)$, road segments with a large standard deviation are penalized. Over such road segments, the vehicular density is not well distributed over adjacent IFTIS cells. This in turn can lead to disconnections compromising the multi-hop packet forwarding along the road. The influence of the weights α and β (equations (6-6) and (6-7)) in the computation of the scores S_i was studied in [57] by means of simulations for varying values of the overall vehicular density in the considered road network. Simulation results showed that when GyTAR is tuned to favor the selection of intersections providing higher progress towards the destination (α=0.8; β=0.2), it obtains higher performance with higher vehicular densities. On the contrary, when GyTAR favors the selection of roads exhibiting higher vehicular density (α=0.2; β=0.8), it works better for lower vehicular density scenarios. Using an intermediate configuration (α=0.5; β=0.5) was shown to provide good performance under all the evaluated vehicular density scenarios. For this reason, the authors of [57] claimed that using such intermediate configuration is always a reasonable choice.

6.4.2 Improved sender-based forwarding and recovery strategy

Once GyTAR has selected the next target intersection, the packet is transmitted towards this intersection by adopting an improved sender-based greedy forwarding method. This method consists in choosing as next forwarder the neighbour node that at the moment of the transmission is expected to be within the sender’s communications range, while at the same time providing the highest progress towards the targeted intersection. For this purpose, similarly to TOPOCBF, GyTAR packets carry the geographical coordinates of the addressed intersection. To select the next forwarder, the packet sender analyzes the location table entries relative to its neighbours. For each neighbour, these entries contain the position, velocity, heading direction, and timestamp at which this information was last stored. By processing this information, the sender estimates the positions of the neighbours at the time of transmitting the packet. Among these neighbours, the one placed within the communications range, and providing the highest progress towards the targeted intersection is selected as next forwarder. The advantage of this approach is supposed to be twofold. Firstly, this mechanism is expected to add robustness to packet forwarding given that it only selects next forwarders that can be reliably reached. Secondly, it is supposed to reduce the end-to-end latency given that subsequent forwarders are always chosen as those providing the longest hops.

Although GyTAR’s improved sender-based greedy forwarding strategy adds robustness to packet transmissions, the risk remains that a packet reaches a local maximum. To address this type of situations, a simple store, carry and forward recovery strategy is used by GyTAR. A vehicle detecting itself as a local maximum carries the packet to the next target intersection. In case it is not driving in that direction, it carries the packet until it gets in contact with a vehicle providing progress towards the targeted intersection. As soon as this vehicle enters in the carrier’s communications range, it is selected as next forwarder. Therefore, it receives the packet via a unicast transmission.

6.5 Performance evaluation

This section describes the performance of TOPOCBF in its capability to route packets using consecutive multi-hop connected road segments detected in real time by the DiRCoD mechanism. The evaluation of TOPOCBF has been performed through simulations and using GyTAR as benchmark for comparison. Before showing the simulation results, the section describes the scenario considered for the evaluations and the adopted performance metrics. The section also describes how design parameters of both TOPOCBF and GyTAR have been tuned to ensure their best performance in the analyzed scenarios.

6.5.1 Simulation scenario

Performance evaluations have been made through simulations over the iTETRIS version of the ns-3 simulator described in Section 4.4. Like DiRCoD and IFTIS, TOPOCBF and GyTAR operate at the Transport & Network layer of the ETSI ITSC Architecture (Section 2.3), and hence their implementation can be limited to ns-3 only. To simulate the operation of TOPOCBF and GyTAR, ns-3 does not require interactions with the rest of the iTETRIS blocks. Vehicles' positions at every instant are obtained by ns-3 by reading vehicular traces generated by SUMO. The radio propagation effects that have been shown in section 6.3.4 and 6.3.5 to possibly influence the operation of the TOPOCBF schemes in urban scenarios are realistically modelled in the adopted version of ns-3.

The conducted simulations aim at reproducing the routing of a GeoUnicast notification message from an originating vehicle to a fixed node. Without any loss of generality, and just to ease the implementation of the protocols, a Manhattan-like road network has been considered for the evaluations. The operation and performance of TOPOCBF are in fact expected to hold in more generic road networks whose representation can be translated into to a set of road segments and intersections. The adopted Manhattan-like road network is depicted in Figure 6-7. It consists of a grid of streets crossing each other perpendicularly. The grey blocks between these streets represent buildings. The shielding effect of buildings to radio propagation impair communications between vehicles placed at perpendicular or parallel road segments. Road segments with different lengths, number of lanes and vehicular densities are emulated. In particular, the shaded roads in Figure 6-7 represent streets with 3 lanes (2 in one direction, and 1 in the other). The other streets only have 2 lanes in total. Road intersections are not regulated by traffic lights, except the intersection between the two 3-lanes roads. Realistic traffic mobility is emulated by letting SUMO feed ns-3 with vehicular traces in which the maximum allowed speed is 50 km/h. Four different vehicular traffic scenarios have been simulated and categorized according to the "Level of Service" (LOS) metric proposed by the Highway Capacity Manual (HCM) [156]. This metric represents a quality measure to describe the operational conditions within a highway vehicular traffic stream, and is retrieved by analyzing the experienced average driving speed and vehicular density. Six different levels of service are defined, with LOS A representing free-flow conditions up to LOS F describing severe congestion situations.

For urban scenarios, the Skycomp Company has classified the LOS metric based on the number of vehicles in observed platoons [157]. In this context, the first simulated scenario (Scenario 1 in the following) is characterized by an average vehicular density of 6 vehicles/km/lane for all the streets. According to Skycomp's definitions, this density results in a LOS A ("very light traffic") since almost no queues or platoons are present at road intersections. Scenario 2 is characterized by a vehicular density of 10 vehicles/km/lane over the streets having 3 lanes (shaded roads in Figure 6-7). This density results in platoons of less than 15 vehicles corresponding to a LOS C ("moderate traffic") for the streets with 3 lanes, while the other streets still experiences LOS A. The third scenario (Scenario 3) has a vehicular density of 10 vehicles/km/lane for the streets with 3 lanes (LOS C), and of 8 vehicles/km/lane in the other streets. This last density results in platoons of a few vehicles at intersections, which corresponds to a LOS B ("light traffic") in the Skycomp classification. Finally, Scenario 4 corresponds to an average vehicular density of 10 vehicles/km/lane in all the streets, reproducing a uniform LOS C over the complete road network. For all the scenarios, the positions of the GeoUnicast packets' source (S) and destinations (D_1 or D_2) have been fixed as shown in Figure 6-7. This configuration allows better comparing how TOPOCBF and GyTAR are differently influenced by the spatial distribution and density of the vehicular traffic in the road network.

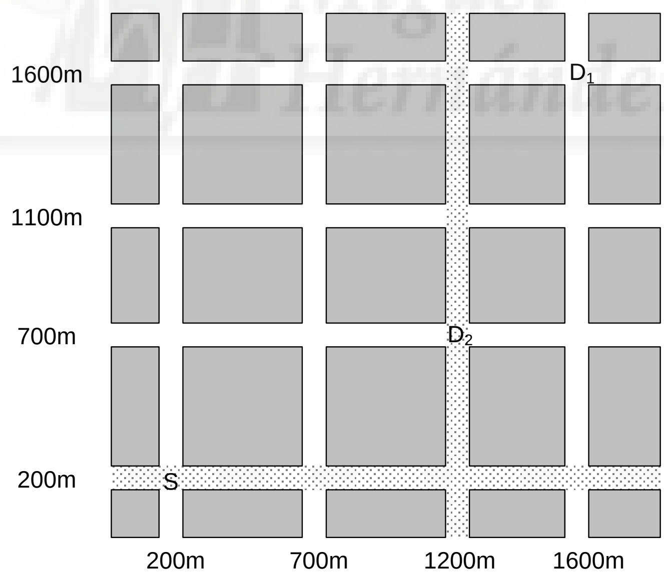


Figure 6-7. Urban Manhattan-like scenario.

In the presented urban scenario, vehicles communicate using 5.9GHz ETSI ITS G5A radio interfaces, and transmit on the control channel (G5CC) at the default 6Mbit/s data rate scheme of the ITS G5 standard [12]. GeoUnicast notification messages are issued by the source S at a rate of 1Hz. In addition, every vehicle generates beacon messages with a

2Hz frequency. Four different transmission powers (14, 17, 20 and 23dBm) are adopted to highlight how they impact the performance and operation of the compared schemes. As already remarked in Section 5.5.1, using lower transmission powers augments the number of DiRCoD's road sections and IFTIS' road cells as a result of reducing the experienced communications range. As explained in Section 5.2.2, the vehicles' communications range is defined in this work as the LOS inter-vehicle distance ensuring 99% probability of successful beacon transmissions at a given transmission power. The TOPOCBF parameter p_{max}, defined in Section 6.3.3 as the maximum distance at which a vehicle is expected to receive a packet, also depends on the used transmission power. In this context, the values of the communications range and the parameter p_{max} deriving from the above mentioned transmission powers are in this section the same as used in Chapter 5, and reported in Table 5-1. Finally, the parameter t_{max} defined in Section 6.3.3 as the maximum duration of the TOPOCBF's forwarding timeout has been set to 0.1s.

The operation of TOPOCBF and GyTAR depend on the reception of DiRCoD's *CFs* and IFTIS' *CDPs*, respectively. Section 5.5.1 already explained how DiRCoD and IFTIS transmissions can be implemented using standard GeoNetworking packets. For the evaluation of TOPOCBF and IFTIS, DiRCoD and IFTIS transmissions have been implemented with the same packet formats and sizes as detailed in Section 5.5.1. The simulated TOPOCBF and GyTAR packets also comply with the format defined by ETSI for GeoNetworking transmissions [33]. Based on this format, the TOPOCBF and GyTAR protocols adopt a standard GeoUnicast packet with a payload of 300 bytes. In the GeoNetworking header, both TOPOCBF and GyTAR add 8 bytes to represent the position of the next intersection to target: 4 bytes to code the latitude, and 4 bytes to represent the longitude of this intersection. In TOPOCBF, these 8 bytes correspond to the *NIF* field (Figure 6-3). In the eTOPOCBF variant, both *NIF* and *PIF* are present in the routed packet (Figure 6-6). As a result, for eTOPOCBF packets it is required an additional number of 16 bytes. The packet ID used by TOPOCBF to identify packet duplicates corresponds to the sequence number (SN) present in the standard GeoUnicast extended header (see Table 2-4).

The results reported in the following have been obtained through simulations with an accuracy equivalent to relative errors below 0.05.

6.5.2 Performance metrics

As previously mentioned, this section is aimed at comparing TOPOCBF and GyTAR in their capability to effectively and efficiently route packet over road segments whose forwarding capabilities are detected in real time by the DiRCoD and IFTIS mechanisms. To better highlight this capability, the store, carry and forward recovery mechanism used by GyTAR in case of local maxima is not considered. For a fair comparison of GyTAR to TOPOCBF, it is also considered that in case a vehicle receives a packet at an intersection where it does not hold any IFTIS estimation on the vehicular density of adjacent road segments, the packet is dropped. For the performance comparison, the following performance metrics have been used:

- *Packet delivery ratio (PDR):* defined as the percentage of packets that a routing protocol can successfully deliver to the final destination with respect to the total number of packets transmitted by the source node.
- *Average communications overhead:* represents the average communications overhead (in bytes) generated to correctly route a packet towards its destination. The overhead is computed considering not only the transmission of the routed packets, but also the additional overhead required for the real time assessment of the road segments' forwarding capabilities. In this context, TOPOCBF's overhead also includes the overhead generated by DiRCoD's *CFs*. Similarly, GyTAR's overhead also considers IFTIS' *CDP* transmissions. The average overhead is obtained by dividing the overall measured overhead by the number of packets generated by the source node.
- *Average end-to-end latency:* represents the time (in seconds) needed for a routed packet to reach its final destination. For each packet correctly received by its destination, the end-to-end latency is computed as the difference between the reception time and the time at which the packet was issued by the source node. The average end-to-end latency is retrieved by averaging on the total number of packets successfully delivered to the destination.
- *Average hop length:* defined as the average distance separating a pair of consecutive packet forwarders. For the computation of this distance, the actual vehicles positions at the time of the transmission are considered. These positions are retrieved from the simulation environment. The average hop length is computed considering the total number of successful packet transmissions.
- *Average number of hops:* defined as the average number of times that a routed packet needs to be forwarded before being received at the destination node. The average is computed considering the total number of packets successfully delivered to the destination.

6.5.3 Protocols' optimization

A preliminary simulation-based optimization analysis has been conducted to identify mechanisms and design parameters that maximize the performance of the compared routing schemes. For this evaluation, the vehicular traffic Scenario 4 (see Section 6.5.1) has been adopted, with vehicles communicating at a transmission power of 23 dBm (200mW). The destination node for GeoUnicast transmissions has been set to D_1 in Figure 6-7.

6.5.3.1 TOPOCBF optimization

TOPOCBF selection of intermediate target intersection depends on DiRCoD's capability to provide vehicles at intersections with up-to-date connectivity information. As demonstrated in Section 5.5.3, this capability is influenced by the DiRCoD's *CF generation period*. The *CF generation period* determines the periodicity of DiRCoD's road connectivity assessments. Lower values of this period result in that vehicles at intersections receive DiRCoD connectivity estimates more frequently. Figure 6-8 depicts how TOPOCBF's PDR and average communications overhead vary as a function of this parameter. For this evaluation, the intersection zone radius *R* has been set to 30m, while the Connectivity Expiry Time (*CET*) is 0.5s higher than each considered *CF generation period*. The depicted results show that, using a DiRCoD's *CF generation period* of 2s is enough to efficiently provide TOPOCBF with useful road connectivity information, and for this reason it has been adopted for the next evaluations. Using a value of 1s doubles DiRCoD's communications overhead (Figure 6-8b) without improving TOPOCBF's packet delivery performance (Figure 6-8a). On the other hand, increasing the *CF generation period* to 3s only slightly reduces DiRCoD's overhead and generates a degradation of the PDR. As shown in Figure 6-8, the overhead generated by DiRCoD is always much lower than the overhead generated to transmit TOPOCBF packets. By only adding one byte information to standard beacon messages, its impact on the overall overhead gets smaller as the *CF generation period* increases. Interestingly, this effect is hold without considerably compromising TOPOCBF's PDR.

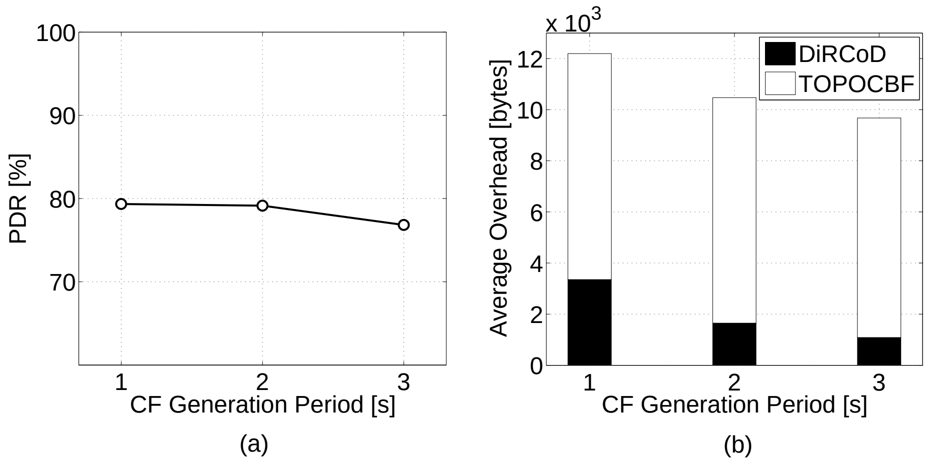


Figure 6-8. TOPOCBF's PDR (a) and average communications overhead (b) as a function of the DiRCoD *CF generation period* (30m *R*; (*CF generation period+0.5)s CET*).

Keeping DiRCoD *CF generation period* to the optimal value of 2s, TOPOCBF's performance has been evaluated for increasing values of the intersection radius *R* and the Connectivity Expiry Time (*CET*). In this context, Figure 6-9a shows that by keeping fixed the *CET*, intermediate values of the intersection zone's radius *R* (30m) results in higher PDR values. For lower values of *R*, the intersection zones depicted in Figure 6-2 get smaller. In these cases, vehicles crossing the intersection zones have less time to receive DiRCoD *CFs*, and consequently might not be capable to select next target intersections properly. On the contrary, with a radius of 35m, the probability that a vehicle has to select the next target intersection far from the intersection zone's center increases. In such cases, the vehicle may have not received any DiRCoD's *CFs* yet, and hence may have no means to select the next intersection. Figure 6-9a also indicates that for fixed values of the radius *R*, increasing the *CET* augments the PDR. Using higher *CET* values gives TOPOCBF the possibility to forward packets at intersections even if DiRCoD connectivity estimates have not been updated very recently. As depicted in Figure 6-9b, the increase of the PDR is achieved at the expense of increasing the average communications overhead. Combining intermediate values of *R* and high values of *CET* further optimizes TOPOCBF's performance. As depicted in Figure 6-9a, the best combination is achieved with *R* set to 30m and *CET* to 6.5s, where the PDR reaches a value of 90.5%. This configuration has then been used for the TOPOCBF performance evaluations described in the following. Using higher values of *R* combined to a high *CET* basically leads to a higher generation of DiRCoD *CFs* that augments the overall average communications overhead (Figure 6-9b) without increasing the PDR (Figure 6-9a).

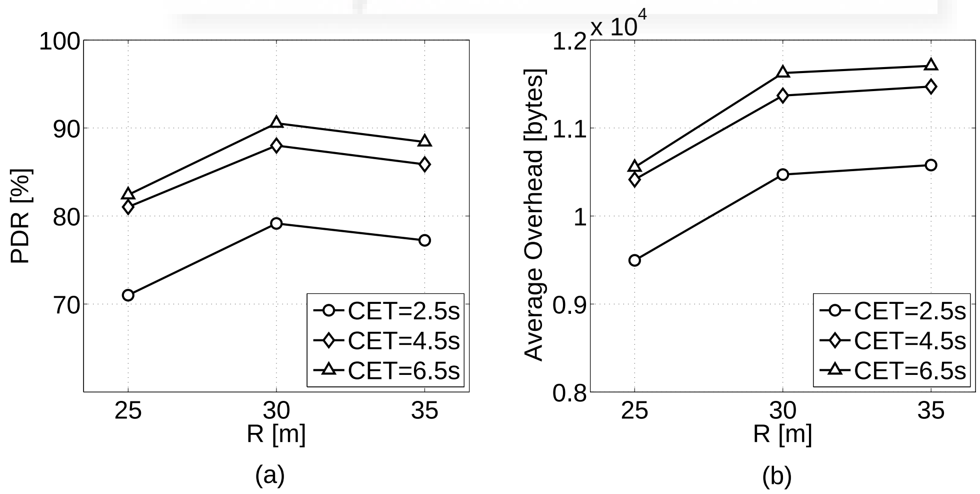


Figure 6-9. TOPOCBF's PDR (a) and average communications overhead (b) for varying values of *R* and *CET* (2s *CF generation period*).

6.5.3.2 GyTAR optimization

GyTAR relies on IFTIS' vehicular road density assessments to select intermediate target intersections. As a result, IFTIS protocol parameters have been tuned as explained in Section 5.5.1. Based on IFTIS' vehicular density assessments, GyTAR selects the next intersection i computing the score S_i as detailed by the equations (6-5), (6-6), and (6-7). The optimization of the parameters α, β and N_{con} of these equations is out of the scope of this work. [57] demonstrated that these parameters should be respectively set to 0.5, 0.5, and 12 in order to allow optimal performance.

In this study, the simulation of GyTAR was performed considering realistic radio propagation models. The simulation results depicted in Figure 6-11a demonstrate that with these models GyTAR's improved sender-based forwarding scheme ("GyTAR" in the figure) results in very poor PDR performance. To understand the reasons of this poor performance, Figure 6-11b analyzes the cause of packet losses. Packet losses are classified into losses due to local maxima ("Local Max"), radio transmission errors ("TX Error"), and lack of any IFTIS vehicular density information at intersections ("IFTIS"). GyTAR limits the choice of the next forwarder to only the neighbours that are estimated to be within the sender's communications range at the moment of the packet transmission. However, in many cases no such neighbours are present in the considered communications range. As a result, GyTAR experiences situations of local maxima, and drops its packets. Removing the limitation of only considering candidate neighbours within the communications range resulted in a zero PDR, as in this case packet forwarding is operated most of the times over very unreliable links. To overcome the above mentioned limitations, two variants of the GyTAR's sender-based forwarding scheme have been introduced. Both variants do not restrict the choice of the next forwarders to neighbours within the sender's communications range. On the contrary, they try to estimate the reliability of radio links in a different way. In the first variant, referred to as "GyTAR a", a vehicle removes a neighbour from its location table if no beacon is received from it for a period of 1.5s. In this case, the only candidate forwarders are those that have proven to be reachable in the very last period. In the second variant referred to as "GyTAR b", a neighbour is stored in the location table for 5s. The next forwarder is selected among the neighbours that are considered "reliable" following the neighbour reliability definition given in 5.3.3. According to this definition, a neighbour is considered reliable if at least 4 beacons have been received from this node in the last 4s, with the last beacon reception being not older than 1s. As it can be noticed in Figure 6-11, adopting these variants improves the delivery performance of the original GyTAR, as a result of considerably reducing the percentage of packet losses due to local maxima. For this reason, GyTAR a and GyTAR b variants are the schemes adopted for comparison with the TOPOCBF protocols.

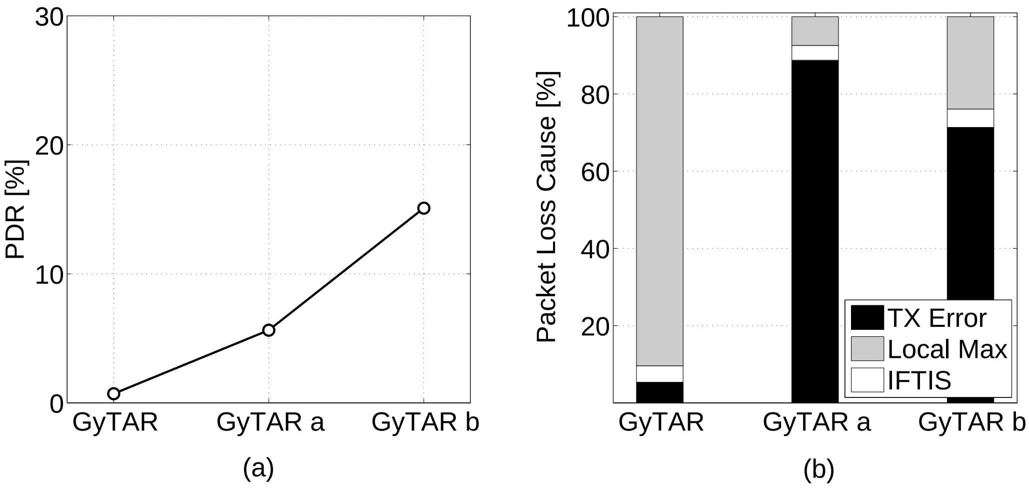


Figure 6-10. GyTAR's PDR (a) and packet loss cause (b) for different variants of the adopted sender-based forwarding scheme.

Figure 6-11 compares the average communications overhead (in bytes) produced to route GyTAR packets with the three considered variants. This overhead accounts for the overhead caused by IFTIS' *CDP* transmissions, and for that generated to forward GyTAR packets. As it can be observed, when running GyTAR most of the overhead is provoked by IFTIS due to the adoption of its dedicated GeoNetworking packets (*CDPs*). This dominant effect of IFTIS implies that the differences in the overall overhead caused by the three compared GyTAR variants are minimal. In fact, although providing visible PDR differences (Figure 6-10a), the average overhead generated by the original version of GyTAR is only 3.6% less than that caused by the GyTAR b variant (Figure 6-11).

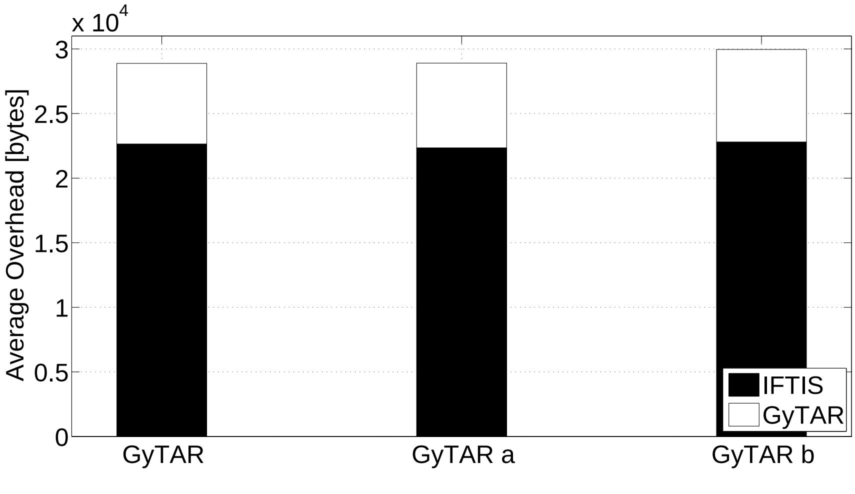


Figure 6-11. GyTAR's average overhead for different variants of the adopted sender-based forwarding scheme.

6.5.4 Performance comparison

In this section, the performance of TOPOCBF and GyTAR are compared by separately considering the effects of different vehicular traffic conditions, transmission powers, and distances between packet's source and destination.

6.5.4.1 Effect of vehicular traffic conditions

The performance of the compared routing protocols is first evaluated as a function of the four vehicular traffic scenarios defined in Section 6.5.1. The transmission power has been set to 23 dBm (200mW). The destination node has been set to D_1 in Figure 6-7.

Figure 6-12 compares the achieved Packet Delivery Ratio (PDR). The TOPOCBF schemes exploit DiRCoD's real time connectivity estimates to forward packets over subsequent multi-hop connected roads. They achieve higher PDR performance due to DiRCoD's capability to continuously provide vehicles at intersections with up-to-date road connectivity information, and due to the increased reliability of the adopted broadcast forwarding scheme. Since TOPOCBF cannot totally prevent from duplicating packets at intersections, it can create parallel forwarding paths that increase the possibilities to reach the final destination. As a consequence, it results in a slightly higher PDR compared its eTOPOCBF variant. However, this PDR difference tends to disappear under dense vehicular traffic scenarios (e.g. Scenario 4) where more road segments can be multi-hop connected. The lower PDR performance of the GyTAR schemes is caused by three reasons. The first is that IFTIS is not always able to inform vehicles crossing intersections with up-to-date vehicular density of adjacent road segments. The second is the possibility to get blocked in local maxima, and the third is the vulnerability of the adopted sender-based forwarding scheme under large and rapid signal level variations. Even if more robust variants are used to select the next forwarder (e.g. "GyTAR b" in Figure 6-12), GyTAR's performance is still significantly lower than TOPOCBF. GyTAR's packet losses are due to different factors depending on the considered traffic scenario. This behavior is shown in Figure 6-13 considering the GyTAR b variant. In the scenario with the lowest vehicular density (Scenario 1), packets losses are mostly due to the lack of any IFTIS density information at intersections, or because the packet reaches a local maximum over a given road segment. In total, these two factors account for 92% of packet losses. As demonstrated in Section 5.5.3, with low vehicular density IFTIS' *CDPs* are not frequently received at intersections. Consequently, vehicles that have to route a GyTAR packet at intersections either do not hold any vehicular density information about the adjacent road segments (and thus drop the packet), or hold outdated information that may not represent the current roads' density status (and forward the packet towards local maxima). On the other hand, the majority of packet losses in the scenario with the highest vehicular density (Scenario 4) is due to radio transmission errors (70% of the total losses).

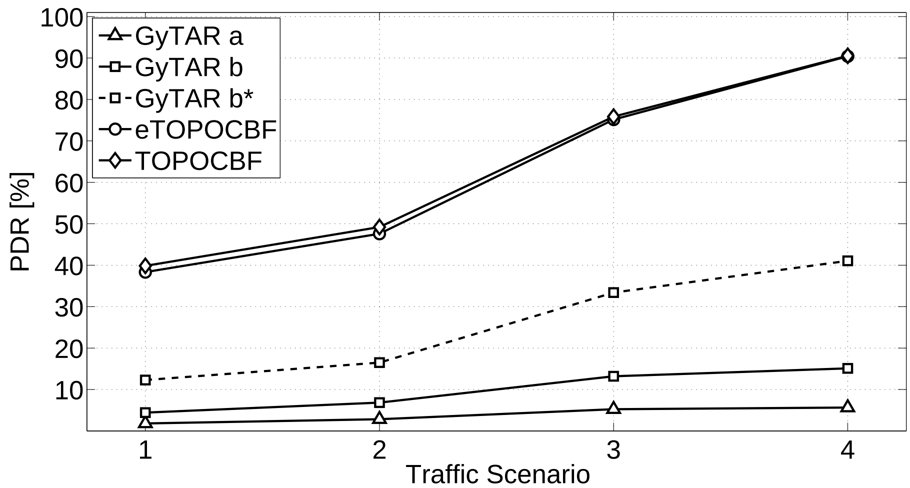


Figure 6-12. PDR for the four simulated traffic scenarios (23dBm transmission power).

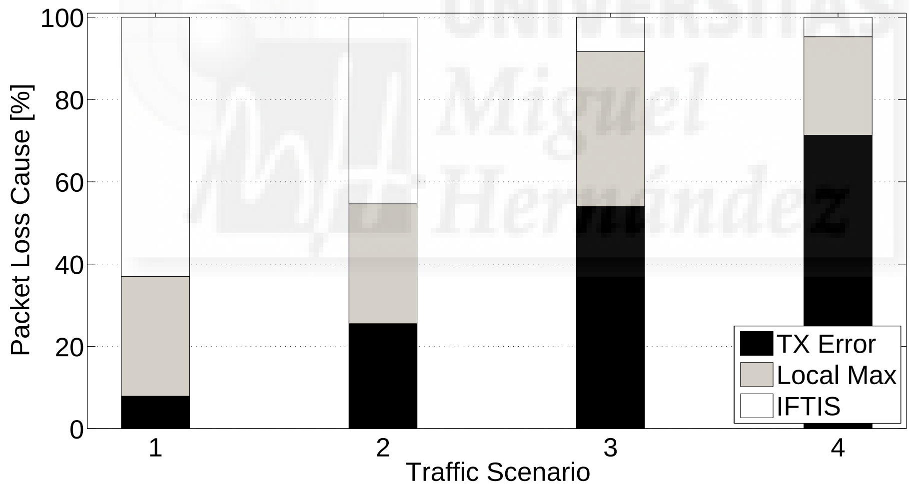


Figure 6-13. GyTAR b's packet loss cause for the four simulated traffic scenarios (23dBm transmission power, WINNER B1 propagation model [147]).

Despite not being supported by its store, carry and forward recovery mode, GyTAR exhibits a significantly lower PDR performance compared to the results presented in [57]. To understand the reasons of this behaviour, GyTAR has also been evaluated using simulation settings trying to approximate those indicated in [57]. To this aim, the performance of the GyTAR b variant has been evaluated using a simplistic Two-Ray Ground Reflection propagation model [158] and a 3dBm transmission power ("GyTAR b*" in Figure 6-12). Following the communications range's definition adopted in this study, these settings result in a much higher communications range (255m compared to the 115m considered in this section, which results from adopting a more realistic propagation model and a transmission power of 23dBm). As shown in Figure 6-12, under a simplified propagation modelling GyTAR b* acquires more robustness and provides higher PDR values over all the studied traffic scenarios. This is confirmed by Figure 6-14 that shows considerably lower percentages of packet losses due to transmission errors compared to those showed using more realistic propagation models (Figure 6-13). Under the simplified model, GyTAR b* losses are mostly due to not finding any reliable neighbour in the location table at the moment of selecting the next forwarder (local maximum).

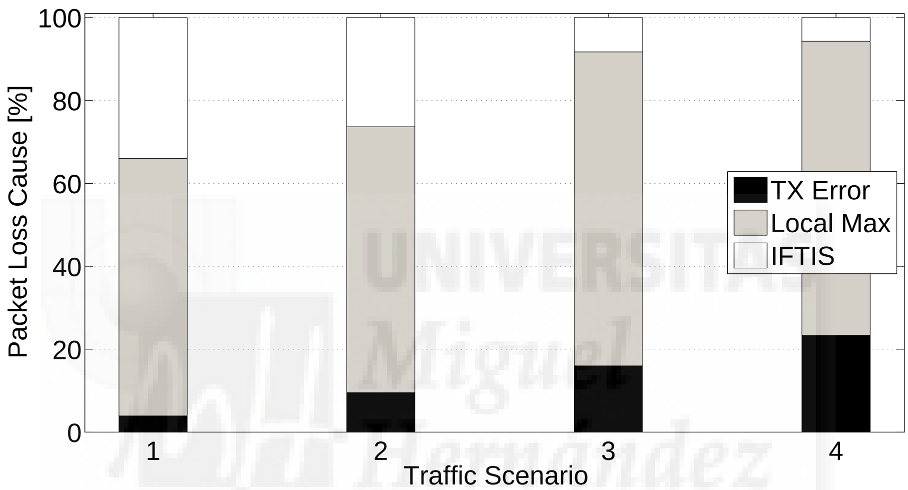


Figure 6-14. GyTAR b*'s packet loss cause for the four simulated traffic scenarios (3dBm transmission power, Two-Ray Ground Reflection propagation model [158]).

Figure 6-15a compares the protocols' average communications overhead (in bytes). The results show that even if GyTAR is able to only deliver a small percentage of packets to the destination, it always generates a higher average communications overhead compared to TOPOCBF. This is due to the significant overhead generated by IFTIS (that on average represents 73% of the overall GyTAR's overhead), and to the many packet retransmissions at link level resulting from unicast transmission failures. The simplistic propagation model considered for GyTAR b* increases the links' reliability and reduces the number of packet retransmissions. Consequently, the average communications overhead is reduced compared to that produced using more realistic propagation models. In particular, GyTAR b* generates on average 9% less overhead than GyTAR b. The TOPOCBF schemes rely on broadcast packet forwarding and hence do not use retransmissions at link level. Moreover, they require a relatively low amount of communications overhead for road connectivity estimation. Over the studied traffic scenarios, DiRCoD generates on average only 14% of the overall TOPOCBF's overhead. This results in that TOPOCBF generates up to 61% less average communications overhead than GyTAR b in Scenario 4. As previously explained, eTOPOCBF was designed to prevent packet duplications at intersections and the generation of parallel forwarding paths, especially in traffic scenarios characterized by high vehicular density. This results in that eTOPOCBF reduces the average overhead by up to 12% compared to TOPOCBF under traffic Scenario 4 (Figure 6-15b). The results reported in Figure 6-12 showed that this overhead gain is obtained without compromising the PDR performance. In conditions of high vehicular density, exploiting parallel forwarding paths does not bring any advantages in terms of PDR, but rather consumes precious channel resources. In this context, the results shown in Figure 6-12 and Figure 6-15 confirm that eTOPOCBF is the most suitable scheme in conditions of high vehicular traffic.

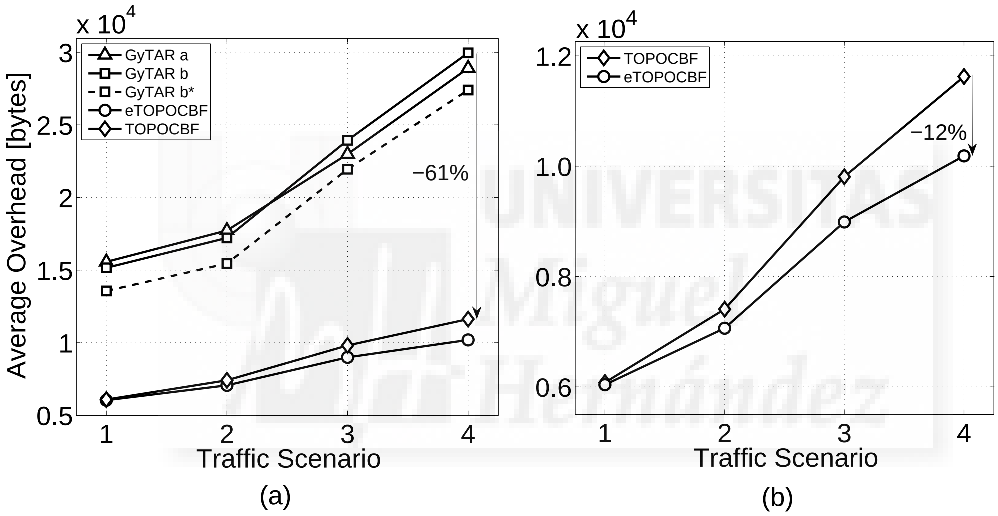


Figure 6-15. Average communications overhead for the four simulated traffic scenarios (23dBm transmission power).

Chapter 5 indicated that estimating the road segments' forwarding capability directly through multi-hop road connectivity rather than using vehicular density could help distributing the routed packets more uniformly over the road network. This would avoid always loading and eventually congesting the communications channel over roads experiencing higher traffic densities. To analyze this effect, Figure 6-16 represents for GyTAR b (a) and TOPOCBF (b), the spatial distribution of the packet forwarding probability over the simulated road network. This probability is computed by dividing the road network in square cells of 30m*30m. Each bar accounts for the packet forwarding events that have taken place on a given cell. The results illustrated in Figure 6-16 correspond to the traffic Scenario 2 in which the 3-lanes road from point (200, 200) to point (1600, 200) experiences a much higher vehicular density than the 2-lanes road from point (200, 200) to point (200, 1600). Figure 6-16a shows that GyTAR mostly selects the intersection at (700, 200) as next anchor point when a packet is generated at the source node S. In addition, GyTAR tends to forwards the packets over the roads characterized by higher vehicular density (i.e. the road from point (200, 200) to point (1600, 200), and the road from point (1200, 200) to point (1200, 1600)). On the contrary, TOPOCBF distributes the forwarded packets over all the road segments (Figure 6-16b) in a more uniform way. This results from the fact that DiRCoD's multi-hop connectivity does not represent a direct estimation of vehicular traffic density. Thanks to DiRCoD's estimations, TOPOCBF can route packets over road segments that do not experience the highest densities but still ensure good forwarding capabilities. This property allows TOPOCBF to reduce the communications load over the road segments that are more prone to suffer channel congestion. This important benefit is achieved without reducing the PDR performance.

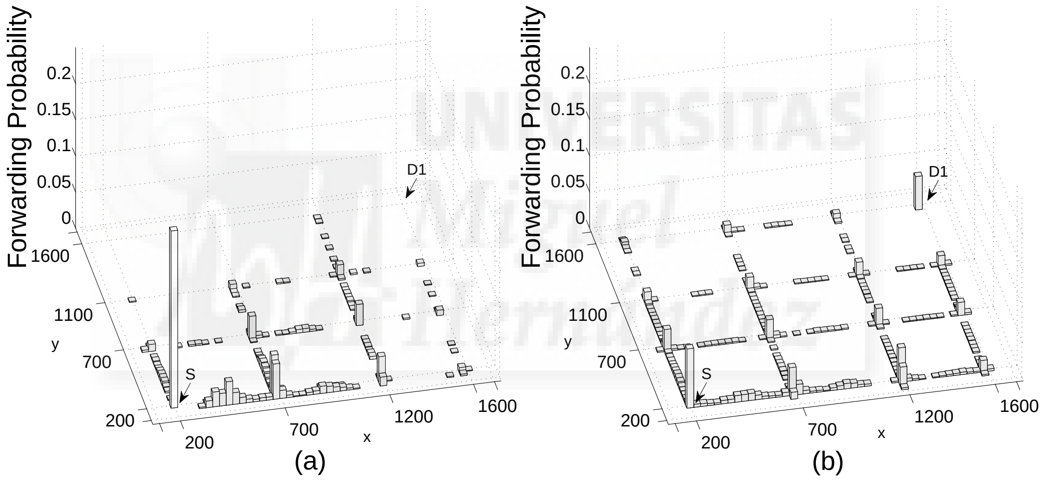


Figure 6-16. Spatial distribution of the packet forwarding probability for GyTAR b (a) and TOPOCBF (b) (traffic Scenario 2, 23dBm transmission power).

6.5.4.2 Effect of transmission power

While the previous results were obtained for a fixed transmission power of 23dBm, this section investigates the impact of varying the transmission power on the protocols' performance. For this evaluation, the vehicular traffic Scenario 3 defined in Section 6.5.1 has been adopted. Other traffic scenarios returned similar results to those shown in the following. As depicted in Figure 6-17, increasing the transmission power augments the PDR of all the protocols. This results from leveraging higher communications ranges and exploiting a higher probability to find forwarders for multi-hop transmissions. The difference between the PDR obtained by TOPOCBF and GyTAR is similar to that shown in Figure 6-12. TOPOCBF always performs better irrespectively of the adopted transmission power and protocol variant. The previous section demonstrated that eTOPOCBF's tends to provide delivery performance similar to those obtained by TOPOCBF in conditions of higher vehicular density. A similar effect is obtained here with a fixed traffic scenario when using a higher transmission power. In fact, for higher transmission powers the local neighbor density experienced by every vehicle is also higher.

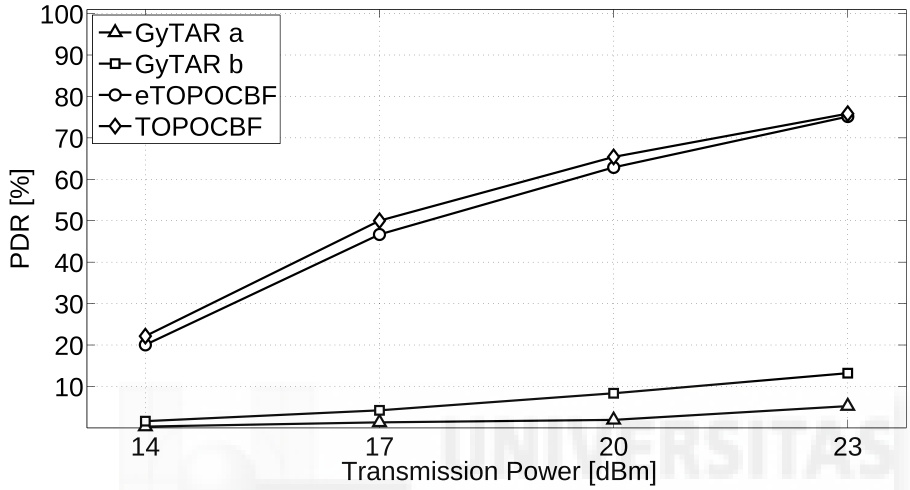


Figure 6-17. PDR as a function of the transmission power (traffic scenario 3).

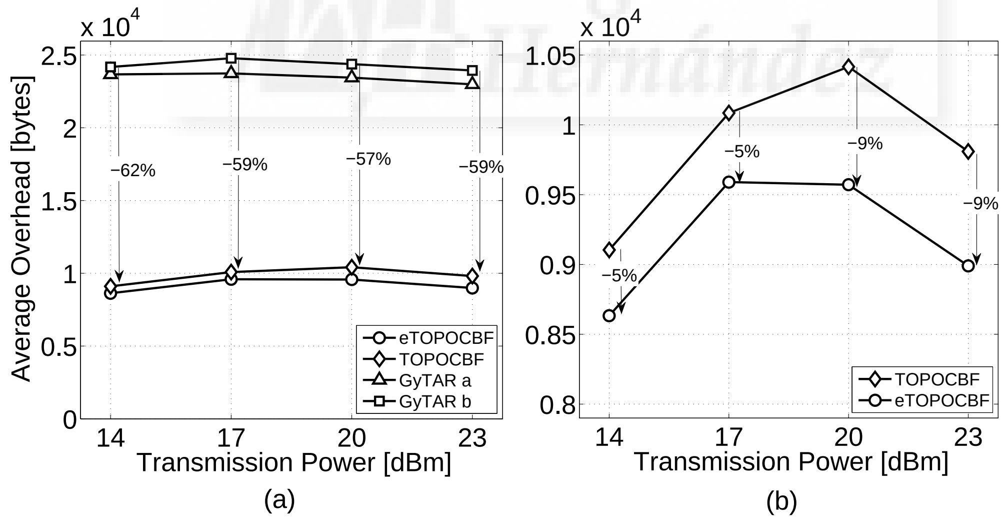


Figure 6-18. Average communications overhead as a function of the transmission power (traffic Scenario 3).

In terms of average communications overhead, Figure 6-18 confirms the lower overhead of TOPOCBF schemes compared to GyTAR, irrespectively of the simulated transmission power. In fact, TOPOCBF reduces the average overhead by more than 57% compared to GyTAR b (Figure 6-18a). eTOPOCBF further reduces the average overhead by up to 9% compared to TOPOCBF (Figure 6-18b). Since this reduction is achieved without affecting its PDR, eTOPOCBF would be the most convenient solution to adopt for this configuration of vehicular density. It is important to note that decreasing the transmission power results in transmitting packets over a higher number of hops with reduced length. However, only a small percentage of them successfully reach the destination. On the contrary, using higher transmission powers implies a lower number of longer hops. In these conditions, more packets are correctly delivered to the destination. As a result, the amount of communications overhead generated by transmitting with lower transmission powers almost equals the overhead produced with higher powers (Figure 6-18a).

The previous results have demonstrated the significant PDR and overhead benefits of TOPOCBF schemes exploiting DiRCoD's multi-hop connectivity information. These benefits are in part due to TOPOCBF's contention-based forwarding approach as opposed to GyTAR sender-based forwarding. As shown throughout this study, a distributed contention-based forwarding naturally adds robustness in the selection of next forwarders. However, this robustness is achieved at the expense of increasing the end-to-end latency resulting from the application of the timeout-dependent TOPOCBF forwarding schemes. As shown in Figure 6-19a, the average end-to-end latency needed by TOPOCBF to deliver a packet from source to destination is always higher than that required by GyTAR. In fact, while GyTAR transmit packets as soon as the forwarder is chosen, TOPOCBF adds at each hop a delay that is needed for the distributed computation of the next forwarder. This delay is the forwarding timeout computed as indicated by equation (6-3). The forwarding timeout ranges from 0 to t_{max} (here set to 0.1s) depending on the progress provided by the forwarder towards the next target intersection. However, the results depicted in Figure 6-19a show that TOPOCBF's end-to-end latency can be significantly reduced as the transmission power augments. By increasing the transmission power, nodes are able to transmit to more distant vehicles, thereby increasing the average hop length (Figure 6-19b) and decreasing the average number of hops (Figure 6-19c) used in the packet forwarding process. As a result, TOPOCBF schemes can considerably reduce their average end-to-end latency, passing from 0.75s using a transmission power of 14dBm to 0.26s using 23dBm. Figure 6-19b shows that GyTAR's sender-based forwarding scheme always results in longer hops compared to TOPOCBF, which reduces the average end-to-end latency (Figure 6-19a). However, longer hops between GyTAR forwarders also reduce the links' reliability, and significantly degrade the PDR (Figure 6-17). This effect is mitigated in GyTAR b that more accurately chooses more reliable forwarders than GyTAR a. This results in that GyTAR b transmits over shorter hops (Figure 6-19b), and achieves better PDR values than GyTAR a (Figure 6-17).

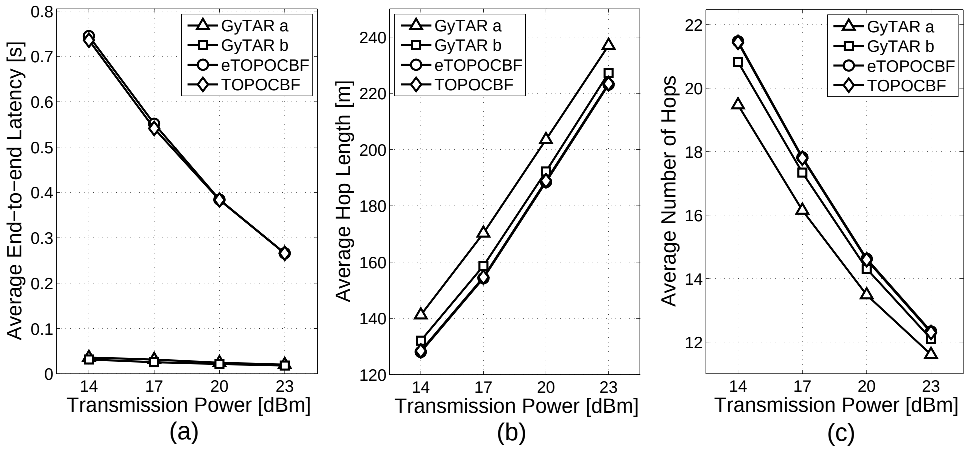


Figure 6-19. Average end-to-end latency (a), hop length (b), and number of hops (c) as a function of the transmission power (traffic scenario 3).

6.5.4.3 Effect of the distance between source and destination

GyTAR's PDR degradation resulting from the unreliable selection of forwarders can increase not only with longer hops, but also with a higher number of hops between source and destination. To analyze this effect, Table 6-1 compares GyTAR and TOPOCBF performance when shortening the distance between source and destination nodes. Considering the road network illustrated in Figure 6-7, the performance obtained with the original destination at point D_1 (referred to as "Long" in Table 6-1) is compared to that obtained with the destination node placed at D_2 ("Short" in Table 6-1). For this evaluation, the traffic Scenario 3 and a transmission power of 23dBm have been considered. Reducing the distance between source and destination nodes decreases the average number of hops necessary to reach the destination to almost 6 hops. As a result, the probability to loss packets along the path decreases for GyTAR schemes, which significantly augments their PDR. However, the same benefit is observed for the TOPOCBF schemes that reach PDR values exceeding 90%. Reducing the distance between source and destination decreases the average communications overhead for TOPOCBF more significantly than for GyTAR. This is due to the fact that most of GyTAR's overhead is due to IFTIS transmissions (see Figure 6-11). The number of IFTIS messages does not vary as the position of the destination changes. As a result, the distance between source and destination does not have a significant impact of the overall GyTAR overhead. On the other hand, most of TOPOCBF's overhead is caused by the forwarding of packets, and is only slightly influenced by DiRCoD (see Figure 6-8b). As a result, shorter distances from source to destination significantly reduce TOPOCBF's average communications overhead.

	Packet Delivery Ratio (%)		Average Communications Overhead (bytes * 10^4)		Average End-to-End Delay (ms)		Average Number of Hops		Average Hop Length (m)	
	Long	**Short**	**Long**	**Short**	**Long**	**Short**	**Long**	**Short**	**Long**	**Short**
GyTAR a	5.23	20.82	2.30	2.17	20.23	8.90	10.83	5.76	237.00	257.81
GyTAR b	13.18	31.79	2.39	2.23	18.20	8.40	11.54	5.87	227.19	252.76
TOPOCBF	75.86	91.54	0.98	0.60	265.55	109.50	11.88	6.19	223.43	239.54
eTOPOCBF	75.15	91.35	0.90	0.53	265.86	109.79	11.84	6.17	223.06	239.08

Table 6-1. TOPOCBF and GyTAR performance for different distances between source and destination (23dBm transmission power, traffic Scenario 3).

6.6 Summary and discussion

This chapter has presented TOPOCBF, a new vehicular routing proposal that uses a dynamic and adaptive contention-based forwarding scheme over road topologies represented as set of road segments and intersections. TOPOCBF iteratively selects its forwarding paths during the routing process based on the multi-hop connectivity of candidate road segments estimated in real time by the DiRCoD mechanism. TOPOCBF is aimed at overcoming the limitations of previous protocols that also operate a dynamic selection of forwarding paths. These protocols adopt distributed estimations of vehicular density that require generating considerable levels of communications overhead. In addition, these protocols use sender-based forwarding schemes which results in the potential unreliable selection of relay nodes. The performance of the TOPOCBF has been analyzed through realistic simulations for different vehicular traffic scenarios, transmission power levels, and distances between source and destination nodes. This performance has also been compared to that obtained by the GyTAR state of the art protocol. The obtained results demonstrate that despite not using any store, carry and forward recovery mode, TOPOCBF is capable to provide high packet delivery ratios while reducing the communications overhead and spatially distributing the communications load over the road network. These benefits are obtained at the expense of a slight increase of the end-to-end delivery latency, although the experienced latency levels are quite low considering the simulated distances between source and destination. TOPOCBF end-to-end latency levels are certainly acceptable for the majority of cooperative ITS applications requiring multi-hop communications.

7

Connectivity-Aware Hybrid V2X Dissemination

While vehicular routing protocols determine routes to transfer messages from a source to a destination, dissemination mechanisms distribute information to multiple recipient vehicles over a target area. Many studies in the literature define dissemination mechanisms only using V2V communications over IEEE 802.11p/ETSI ITS G5 devices. In most of the cases, this choice is aimed at fulfilling the strict latency requirements of certain cooperative applications. However, vehicular dissemination can be performed using various communication technologies among those specified by the ETSI ITSC architecture [28]. The use of multiple heterogeneous technologies permits several advantages. The distinguishing characteristics of individual technologies (e.g. range, latency, data rate, etc.) allow choosing the best communication solution to fulfil the QoS requirements of different dissemination applications. Using distinct technologies for different applications may better balance the communications traffic, and prevent from overloading a single communication system. Having many communication solutions may also help to overcome the unavailability of certain technologies on specific geographical areas. Heterogeneous communication environments can be used for the dissemination of traffic information. In this context, current proposals use either cellular communications or vehicular ad-hoc networks. In the former case, the information to disseminate is transmitted to interested vehicles through individual messages. In the latter one, messages are relayed from source to destination nodes using V2V communications. Dedicated cellular transmissions may pose energy and traffic scalability issues to network operators, and require additional economic cost for the use of proprietary cellular networks. Ad-hoc dissemination solutions may also pose scalability issues if not adequately designed. They would not rely on any proprietary communication infrastructure, and in principle would imply lower costs for service implementation. However, solely relying on the availability of forwarding nodes over vehicular ad-hoc networks may result in network disconnections and lower service reliability.

To address these issues, this chapter presents RoAHD, a novel Road Connectivity-Aware Hybrid V2X Dissemination scheme for vehicular networks. RoAHD combines cellular and vehicular ad-hoc communications following a 2-steps approach. First, a few message copies are injected to specific vehicles through the cellular system, and then these injections are followed by a cooperative multi-hop dissemination in the vehicular ad-hoc network. To ensure that injected message copies are delivered to a large number of vehicles, RoAHD's injection decisions are driven by the knowledge of the global VANET's connectivity context. In previous studies, the V2V connectivity context is built by collecting and processing individual vehicle GPS positions through cellular uplink transmissions. However, this approach could result costly in terms of cellular resources, especially in case of high vehicular densities. Differently from these approaches, RoAHD exploits smart collection techniques of small-sized multi-hop road connectivity information. By processing and analyzing the collected information, RoAHD builds a global multi-hop road connectivity map that is used to operate smart injection decisions. RoAHD's design and features permit ensuring good levels of message delivery in VANETs even in the absence of store, carry and forward mechanisms.

The rest of this chapter is organized as follows. Section 7.1 better motivates the design of the RoAHD's proposal. Section 7.2 provides a comprehensive presentation of the various blocks supporting RoAHD's operation. Section 7.3 describes in detail how these blocks are implemented. Section 7.4 presents the V2X dissemination mechanisms used as benchmark for the evaluation of RoAHD that is given in Section 7.5. Finally, Section 7.6 summarizes this chapter's findings and provides some concluding considerations.

7.1 Motivations

Cooperative ITS data dissemination is expected to support the implementation of various cooperative applications aimed at improving traffic safety and efficiency, or at providing infotainment services to users on the move. Cooperative safety applications like the notification of road hazard warnings generally imply disseminating alarm messages to vehicles in the close surroundings of a dangerous event. The strict latency requirements imposed by this class of applications are generally addressed by relaying alarm messages immediately through V2V transmissions over VANETs. For other application classes, less stringent requirements have to be respected. For example, traffic efficiency applications may require the dissemination of messages to notify vehicles belonging to a given destination area ("relevance area") about traffic conditions (e.g. slowdowns or congestions) occurring in other zones of the road network. In this case, the disseminated messages do not inform vehicles about imminent or close risks, and hence higher latencies can be tolerated. As a result, the implementation of dissemination schemes for these applications is not limited to the use of V2V transmissions over VANETs. In this context, it is possible to exploit the heterogeneous and complementary communication capabilities provided by the radio access technologies of the ETSI ITSC architecture [28]. As previously explained, having multiple communication solutions at disposal provides more flexibility, a better distribution of the communications load, and may increase the robustness of message dissemination.

Current traffic efficiency dissemination proposals generally rely on the adoption of a single communication technology. A first class of proposals (e.g. [159]) use cellular systems as depicted in Figure 7-1. After collecting vehicular traffic information from users on the road network, centralized traffic management centers (TMCs) replicate a notification message over multiple copies, and separately transmit them to vehicles using dedicated downlink transmissions.

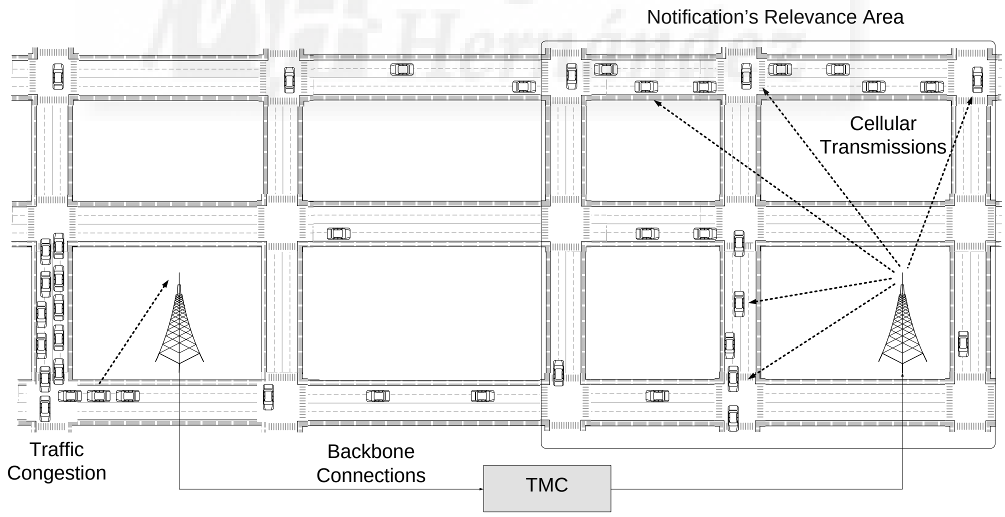


Figure 7-1. Message dissemination using cellular communications.

Other solutions cooperatively relay the notification through VANETs using standard inter-vehicular communications (IEEE 802.11p or ETSI ITS G5). As shown in Figure 7-2, the notification message can be transferred from the source to its relevance area using appropriate GeoRouting protocols. Once in the relevance area, the message can be disseminated within the VANET using V2V communications. In this context, previously proposed V2V dissemination mechanisms optionally use opportunistic store, carry and forward techniques to react against possible VANET disconnections over the relevance area [71][84]. Other proposals leverage the presence of Roadside Units (RSUs) that can serve as originators of the dissemination in the relevance area (similarly to the cellular base stations in Figure 7-1), or as fixed relay nodes to improve the dissemination capability of vehicles [89][160].

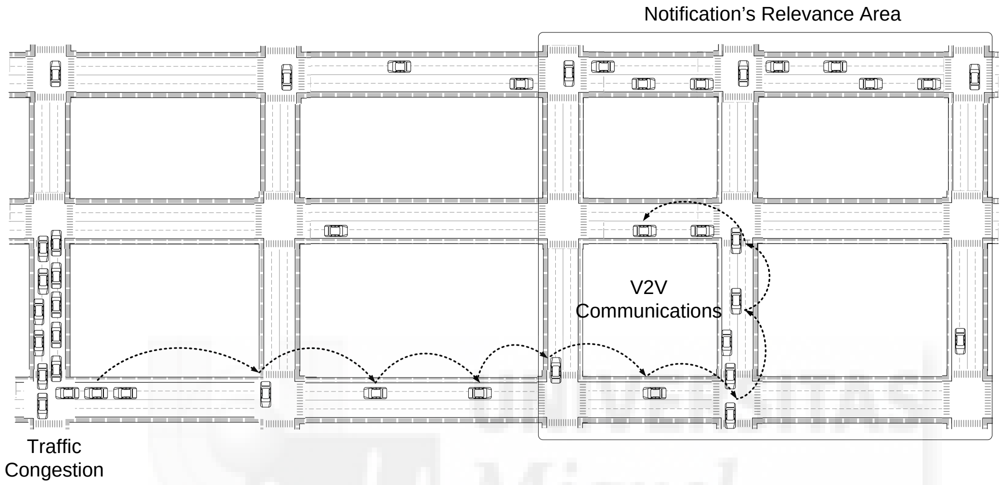


Figure 7-2. Message dissemination using V2V communications.

Using only one communication technology provides advantages but also disadvantages to presented classes of dissemination solutions. The dissemination through cellular systems can exploit extended coverage capabilities to ensure that no vehicle in the relevance area misses the notification. However, with increasing amounts of recipient vehicles, the adopted dedicated cellular transmissions may pose energy cost and traffic scalability issues to network operators nowadays facing a growing demand of mobile data services [161]. Moreover, the use of proprietary cellular networks implies economic costs to either the provider or the users. On the other hand, vehicular ad-hoc dissemination solutions do not rely on any proprietary communication system, and hence would be expected to require less service costs. However, possible VANET disconnections pose a considerable challenge. VANET disconnections may be caused by insufficient presence of relaying nodes in rural areas, or by the uneven distribution of traffic flows and the obstructing effect of buildings to radio propagation in urban scenarios. The effects of such disconnections may highly impair V2V dissemination delivery performances. In some cases, the notification message might not reach at all the relevance zones where it should be disseminated. In other cases, the V2V connectivity conditions of the VANET in the relevance area might not guarantee a complete dissemination of the message over it (see the example in Figure 7-2). Store, carry and forward techniques can mitigate the negative effects of VANETs' disconnections, but generally imply increased delivery delays. If vehicles in distinct and possibly disconnected parts of the relevance area could simultaneously receive the disseminated message, more drivers would have the chance to analyze its content. In this way, more drivers would promptly react to the notified event and hence contribute to maximize the overall traffic efficiency (e.g. in Figure 7-1, vehicles could take alternative routes to avoid the congested zone).

Hybrid V2X dissemination approaches combine the use of cellular and ad-hoc communications. As a result, they can exploit the advantages and mitigate the shortcomings of the previously discussed dissemination solutions. Figure 7-3 illustrates hybrid approaches. In this case, the notification message to disseminate is considered to be held by the TMC. The TMC "injects" a few notification message copies to specific vehicles using cellular downlink transmissions. Upon receiving the injected messages, these vehicles cooperatively disseminate them using V2V communications. Hybrid V2X dissemination strategies may hence provide both cellular efficiency, and vehicular dissemination effectiveness.

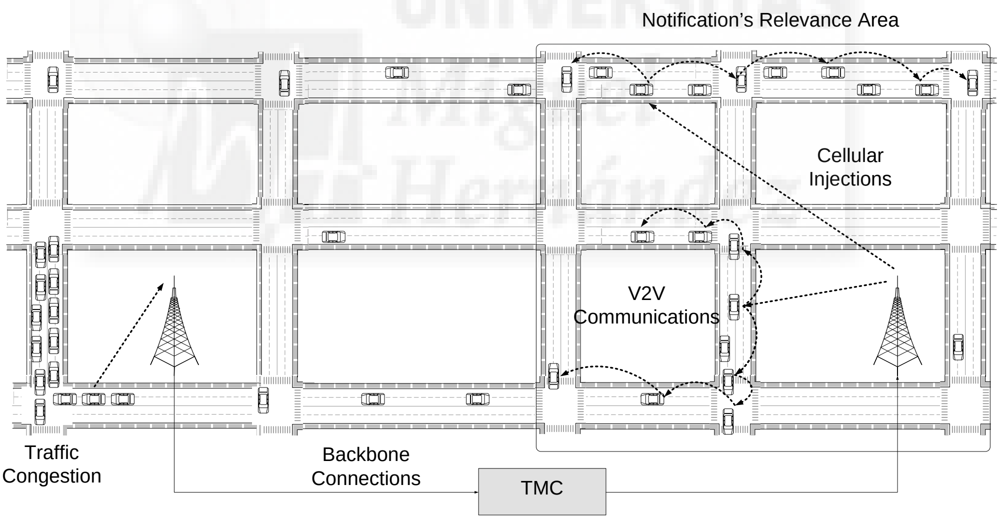


Figure 7-3. Message dissemination using a hybrid V2X communications system.

A very limited number of studies propose vehicular dissemination solutions using hybrid V2X communications. [93] proposes STEID, an emergency dissemination protocol integrating cellular technology with "clusters" of vehicles in the VANET. In each cluster, a clusterhead periodically downloads notification messages, and disseminates them in its cluster. Compared to solutions that only use cellular communications, STEID is proven to reduce the cellular channel load. However, the control traffic needed to form, update, and maintain clusters in the VANET is not evaluated. In [94], the LTE4V2X hybrid framework for the centralized computation of clusters of vehicles is proposed. Based on the information that each vehicle uploads via cellular networks, a centralized TMC computes a “cluster topology”. The cluster topology is defined as the optimal set of clusters in which the VANET has to be partitioned in order to provide stable and reliable intra-cluster V2V communications. Once computed, the cluster topology is communicated to vehicles through the downlink cellular channel. In each cluster, a clusterhead is selected. Clusterheads are in charge of uploading floating car data received from the members of its cluster. In addition, they relay notification messages received from the TMC to clusters that do not have cellular access. Through the use of these clusters, LTE4V2X achieves good delivery levels of both floating car data and notification messages. However, it requires important communications overhead on the cellular channel for the formation, update, and dissemination of the cluster topology. In [96], a “cross-network information dissemination” approach is presented. Based on this approach, a reduced percentage of vehicle acts as VANET’s “gateways” for traffic messages coming from the cellular network. The authors of this study envision estimating the vehicular density by existing cellular traffic data collection mechanisms. Vehicular density estimations are then communicated to gateway vehicles for them to optimize the multi-hop broadcasting protocols used for V2V dissemination. Although very interesting for its design, [96] does not specify how the collected data traffic can be processed to derive useful inputs for the adopted V2V broadcasting protocols. Besides this, it does not explain how gateway vehicles can be selected out of the rest of nodes to ensure optimal performance to the overall V2X dissemination system. Differently from the previous schemes, Push & Track [91] aims at delivering notifications messages to all the vehicles in a relevance area by a service-dependent expiration deadline. For this purpose, the cellular network injects message copies to individual vehicles for them to start disseminating in the VANET using opportunistic V2V communications. A feedback loop in which all the vehicles acknowledge receptions through uplink transmissions permits Push & Track to compute how many message copies have still to be injected and to which vehicle. Through this approach, [91] demonstrated that the highest dissemination delivery performance can be achieved by just injecting a very limited number of message copies whenever a global VANET’s V2V connectivity characterization is held. In fact, by exploiting this context knowledge, message copies can be injected on VANET’s vehicles from where a high number of receivers is expected to be reached.

Inspired by these results, a novel Road Connectivity-Aware Hybrid V2X Dissemination (RoAHD) scheme is presented in this thesis. To comply with cellular channel and energy efficiency requirements, RoAHD considers injecting only a fixed and limited number of message copies in the VANET. To ensure that injected messages are reliably disseminated to large sets of recipient vehicles, it exploits VANET’s V2V connectivity context information. The knowledge of the V2V connectivity context could be obtained by the TMC in terms of spatial distribution of vehicular density. This method is used by solutions such as Push & Track [91] and VISIONS [162]. These solutions periodically collect individual vehicle information such as GPS positions or neighbour lists through cellular uplink transmissions. However, this could be channel costly for the cellular network, especially in case of a high presence of transmitting vehicles. In such cases, periodically uploading individual vehicular information may cause non-negligible negative effects on the other services provided by the cellular operators [163]. To overcome this problem, RoAHD builds the V2V connectivity context using multi-hop connectivity properties of entire road segments. As defined in Chapter 5, the multi-hop road connectivity indicates the capability of a road segment to support reliable and uninterrupted multi-hop transmissions along its length. This information can be directly measured in the VANET using the V2V distributed and channel-efficient DiRCoD mechanism, and then uploaded to the TMC with a much lower cellular channel cost compared to the discussed schemes. The uploaded information is processed and fused to obtain a global connectivity map indicating the road segments that can better support the V2V dissemination. By centrally analyzing this map, RoAHD implements injection strategies to select the vehicles from where the V2V dissemination can reach the highest amount of recipient nodes directly through multi-hop transmissions, and without the assistance of store, carry and forward schemes. To implement such dissemination, RoAHD defines a particular multi-hop protocol that lets vehicles at intersections broadcast the messages. This feature helps to better disseminate messages over any of the road segments composing the targeted area. In this context, RoAHD provides a complete framework for VANET's global connectivity characterization and exploitation compared to the previously proposed hybrid V2X dissemination approaches.

7.2 RoAHD concept

This work considers the presence of centralized Traffic Management Centers (TMCs) implementing cooperative ITS applications, in particular traffic efficiency information applications notifying vehicles driving over specific relevance areas. To implement these applications, a TMC is considered to have access to the deployed wireless communication infrastructure (e.g. UMTS nodes B, WiMAX bases stations, ITS G5 RSUs) by means of backbone connections (see Figure 7-1 and Figure 7-3). The mechanisms through which the TMC generates traffic efficiency notifications are out of the scope of this work. As an example, the TMC could use vehicles as mobile sensors of the vehicular traffic status, collect real time updates, and centrally detect anomalous situations such as congestions or slowdowns [163]. Alternatively, vehicles could cooperatively detect such situations through V2V communications (e.g. like described in [164]-[166]) and inform the TMC. The TMC could be informed through the cellular network (Figure 7-1), or using fixed RSUs.

Assuming that the information to disseminate is already available at the TMC, RoAHD's objective is to disseminate notification messages to the vehicles over a relevance area in an effective and efficient way. In this context, this work considers for the relevance area the same road network representation as introduced in Section 5.2.1, i.e. a set of road segments delimited and interconnected by circular intersection zones. Both the TMC and vehicles are considered aware of such representation by using digital maps. Without any loss of generality, UMTS is considered in this study as the cellular communication technology used by the TMC to implement RoAHD's V2X dissemination scheme. For the centralized dissemination of notification messages over a relevance area, RoAHD uses the V2X hybrid scheme represented in Figure 7-4. The TMC uses UMTS downlink transmissions to simultaneously inject message copies to specific vehicles. These vehicles start then disseminating the message in the VANET through V2V multi-hop broadcast transmissions. RoAHD's goal is to reduce the cellular system's channel and energy consumption by limiting the number of injections, and maximize the message delivery over the target area. To achieve this objective, it leverages a global knowledge of the VANET's V2V connectivity. Through such context characterization, the TMC learns where the injected messages can be safely multi-hop broadcasted in the VANET, and hence delivered to a high number of vehicles. RoAHD defines then different injection strategies that exploit this context characterization.

RoAHD obtains the knowledge of the global V2V connectivity context using multi-hop road connectivity information. The multi-hop road connectivity measures the capability of a road segment to support uninterrupted multi-hop transmissions between its delimiting intersections (Figure 7-4). In a VANET, the multi-hop road connectivity can be estimated in real time by running the distributed and lightweight V2V DiRCoD mechanism presented in Chapter 5. The DiRCoD multi-hop road connectivity information is "sensed" by vehicles placed at road intersections. For example, in Figure 7-5, vehicle C at intersection I_1 would be informed about the possibility to relay a message to intersection I_5 through multi-hop transmissions. RoAHD exploits this capability to make the road connectivity information be uploaded only by vehicles at road intersections (Figure 7-5). In this way, RoAHD can save UMTS uplink channel resources compared to schemes that generate the global connectivity context collecting information from every single vehicle.

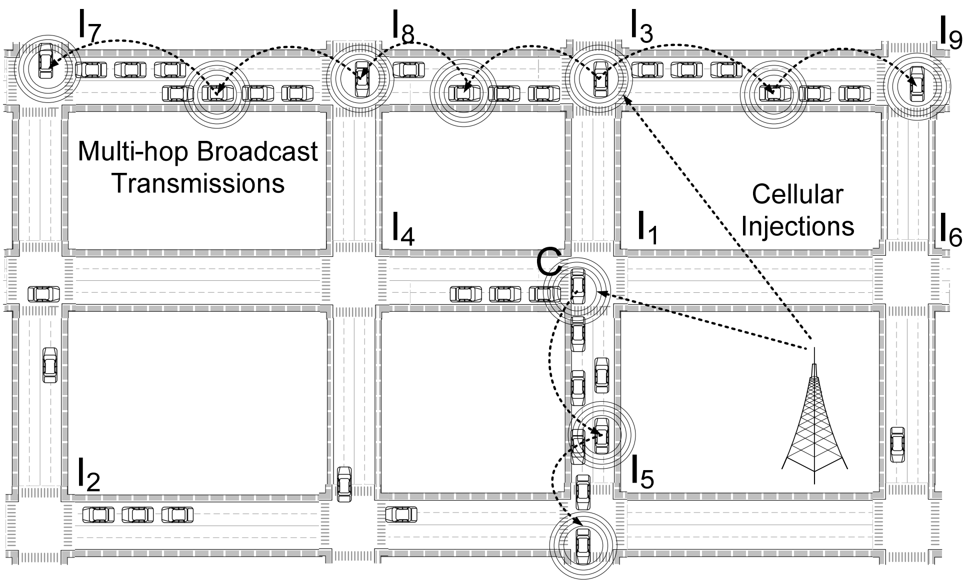


Figure 7-4. RoAHD's hybrid V2X dissemination scheme.

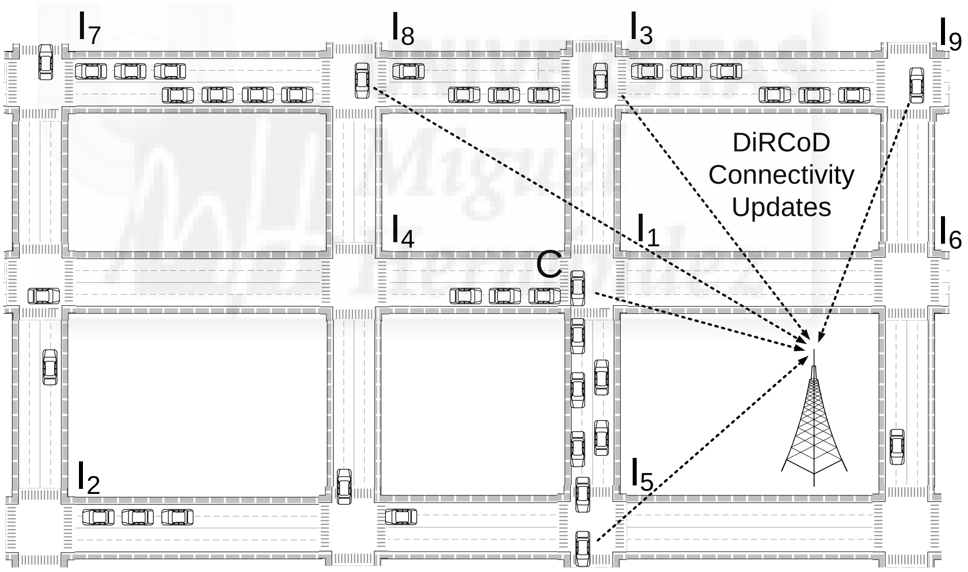


Figure 7-5. RoAHD's uploading of multi-hop road connectivity information.

At the TMC, the DiRCoD connectivity information of every road segment is processed and fused to derive a global V2V multi-hop road connectivity map. By analyzing the multi-hop connectivity of the road segments between adjacent intersections, the TMC computes sets of connected intersections through which a message copy would be reliably multi-hop broadcasted (e.g. the set of intersections I_7, I_8, I_3, and I_9 in Figure 7-4 and Figure 7-5). Moreover, the TMC monitors to which extent the uploaded multi-hop connectivity of road segments is stable over time to derive indications about the vehicular density. In this context, the "*connectivity stability*" is defined as the capability of a road segment to be connected for extended time periods. In fact, roads providing multi-hop connectivity for extended periods can indirectly reflect a higher presence of vehicles.

RoAHD's message injection strategies exploit the obtained connectivity context information to inject the message copies over the road segments showing the highest connectivity stability. Message copies are injected to vehicles at road intersections in order to optimize the V2V dissemination process in the VANET. In fact, injection vehicles at road intersections can exploit Line-of-Sight (LOS) propagation conditions towards various road segments to disseminate the message simultaneously to all the vehicles placed over them. In this context, RoAHD defines and adopts a V2V dissemination mechanism using multi-hop broadcast transmissions through a limited set of broadcasters. These broadcasters are selected in a distributed way according to their capability to provide the message with the maximum progress in any possible direction. A distributed contention-based scheme is implemented to achieve this objective. Based on this scheme, receiving vehicles that are more distant from the previous hops, as well as vehicles that are closer to the centers of still unaddressed road intersections, are selected as next broadcasters (Figure 7-4). A flow diagram summarizing RoAHD's operation is depicted in Figure 7-6.

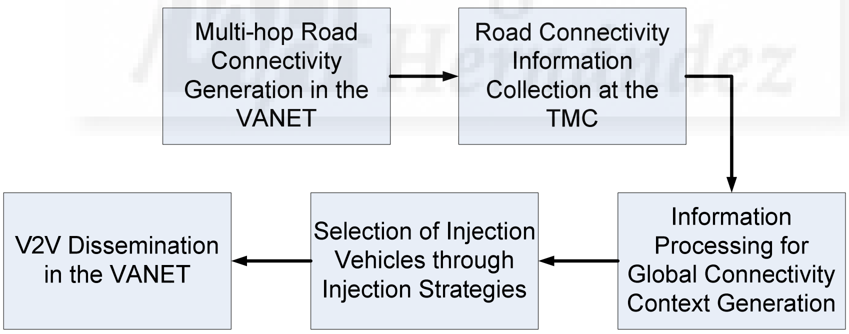


Figure 7-6. Flow diagram of RoAHD's operation.

7.3 RoAHD implementation

This section describes the implementation of RoAHD's hybrid V2X dissemination approach. The different subsections focus on the various steps represented in Figure 7-6. DiRCoD's multi-hop road connectivity generation process has been widely described in Chapter 5. However, some definitions are here briefly recalled to facilitate the understanding of the notation used throughout this chapter.

7.3.1 Collection of road connectivity information

As described in Chapter 5, DiRCoD exploits the inter-vehicular exchange of standard beacon messages to estimate the multi-hop connectivity of road segments, and notify this information to the intersections that delimit them. A vehicle crossing a road intersection I_i overhears the DiRCoD connectivity field CF_{ij} included in the beacon messages received from adjacent road segments I_i-I_j. In this way, it gets informed about the connectivity status of those road segments over the outgoing directions $I_i \rightarrow I_j$. The connectivity status of road segments is expressed in terms of DiRCoD's virtual distance VD_{ij} separating I_i from the intersections I_j. To derive the virtual distance, the road segment is ideally divided into road sections numbered with increasing values starting from I_j (Figure 7-7).

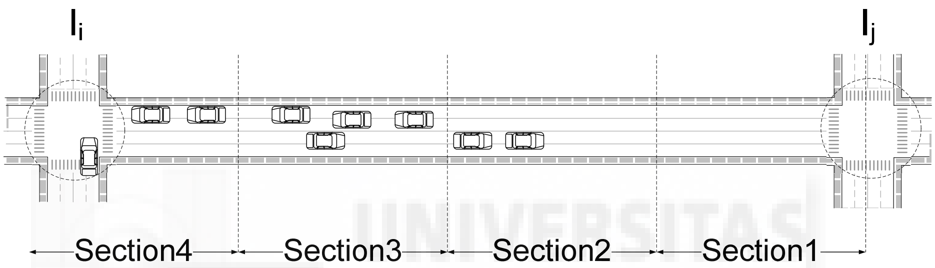


Figure 7-7. DiRCoD multi-hop connectivity estimation over a generic road segment $I_i \rightarrow I_j$.

As defined in Section 5.2.2, overhearing lower VD_{ij} values at I_i indicates that a message from I_i could be multi-hop forwarded to vehicles at closer sections to I_j. In other words, the lower the VD_{ij} contained in CF_{ij}, the higher the multi-hop connectivity status towards I_j. The VD_{ij} sensed at intersection I_i assumes discrete values $\underline{VD}$ in the interval $[0, 1, \ldots, VD_{ijmax}]$. $\underline{VD}=0$ indicates that a message transmitted from I_i would reach a vehicle at I_j directly through multi-hop transmissions (full multi-hop road connectivity status) thanks to the presence of sufficient relaying vehicles. On the contrary, $\underline{VD}>0$ indicates situations in which the message would only reach a vehicle placed at intermediate sections due to the lack of necessary forwarders towards I_j (partial multi-hop road connectivity status, Figure 7-7). $\underline{VD}=VD_{ijmax}$ is the maximum VD_{ij} that can be sensed at I_i, and depends on the road segment's length and the adopted road section's size (e.g. $VD_{ijmax}=4$ in the road segment depicted in Figure 7-7). As defined in Section 5.3.2, a vehicle crossing I_i receives consecutive beacons with appended CF_{ij} every *CF generation period* seconds. The absence of CF_{ij} receptions for longer than this period might imply that last VD_{ij} stored by the vehicle might not represent the actual multi-hop connectivity status of $I_i \rightarrow I_j$.

Considering these definitions, RoAHD uses two techniques to collect DiRCoD information at the TMC, namely the "*Intersection-based"* (IB) and the "*Fast Probing*" (FP) uploading schemes. Both these techniques use cellular uplink transmissions to upload DiRCoD's road connectivity information sensed by vehicles at intersections. This information is uploaded in messages called "*DiRCoD Connectivity Updates*" (*DCUs*). These uploading techniques differ in the content of *DCU* messages and in how uplink transmissions are triggered. A comparison between these two collection schemes will reveal to what extent uploading road connectivity information can be done efficiently in terms of channel resources without compromizing the accuracy of the V2V connectivity context characterization, and the performance of message injection strategies.

7.3.1.1 Intersection-based road connectivity uploading scheme

Let us consider a vehicle running the Intersection-based (IB) uploading scheme and driving through the intersection zone of intersection I_i (circular regions in Figure 7-7). This vehicle uploads a *DCU* message relative to I_i after crossing the center of the intersection, and before leaving the intersection zone. In this case, the *DCU* contains, besides an identifier of I_i, the DiRCoD connectivity information of all the road segments adjacent to this intersection. More precisely, the *DCU* includes the virtual distances VD_{ij} separating I_i from all its adjacent intersections I_j that the vehicle has overheard while crossing I_i. Considering the example of Figure 7-5, vehicle C would upload a *DCU* including an identifier of intersection I_1 along with the overheard VD_{14}, VD_{15}, VD_{13}, and VD_{16}. Before uploading a *DCU*, the vehicle checks, for all the adjacent intersections I_j whether it received a CF_{ij} within the last *CF generation period* seconds. The absence of CF_{ij} receptions in this period indicates that the last overheard VD_{ij} might not represent the actual multi-hop connectivity status of the road segment. As a consequence, the vehicle includes a default VD_{ij} equal to VD_{ijmax} in the *DCU*. The vehicle includes this default value also in case it does not hold any VD_{ij} relative to the road segment (the vehicle did not previously receive any CF_{ij}).

To prevent neighboring vehicles in the VANET from uploading a *DCU* for intersection I_i in the very next instants (thereby avoiding wasting uplink cellular channel resources), the vehicle transmits a standard beacon including an "*Uploading Field*" (*UF*). Vehicles overhearing this field activate a timer of T_U seconds ("*uploading timer duration*") during which prospective *DCU* uploads for I_i are disabled. As a result, the next *DCU* upload for I_i is only executed by the first vehicle crossing the center of I_i with the uploading timer inactive. T_U is hence a parameter that can be configured to control the period between consecutive uploaded *DCUs*.

The IB scheme uploads in *DCUs* a set of VD_{ij} overheard in previous and distinct instants through the reception of beacons with appended CF_{ij}. This results in that the

DiRCoD connectivity information included in IB's *DCUs* might be slightly stale compared to when it is sensed in the VANET. Moreover, higher values of T_U might result in that the TMC does not receive *DCUs* with sufficient frequency to generate an accurate V2V connectivity context characterization. However, vehicular traffic does not generally vary very rapidly. As a result, not uploading *DCUs* very frequently might be enough for the TMC to have a satisfactory image of the instantaneous connectivity context. More importantly, the higher the T_U, the lower the control overhead generated on the cellular uplink channel. In this context, it is necessary to understand to what extent the IB road connectivity uploading scheme can be tuned to correctly leverage the generation of a centralized connectivity map that can be effectively used by RoAHD to inject messages. To analyze such possibility, this study considers as benchmark scheme a Fast Probing (FP) uploading solution.

7.3.1.2 Fast Probing road connectivity uploading scheme

With FP, the upload of *DCU* messages at intersection I_i is triggered by the reception of connectivity fields CF_{ij}. Contrary to the IB scheme, this scheme uploads road segment-specific *DCUs* containing the VD_{ij} included in the received CF_{ij}. Considering again the example of Figure 7-5, vehicle C would upload separate *DCUs* containing VD_{14}, VD_{15}, VD_{13}, and VD_{16} at distinct moments upon receptions of CF_{ij} from the vehicles placed at adjacent road segments. In this way, the DiRCoD connectivity information relative to specific road segments is rapidly made available to the TMC at almost the same moment as it is sensed at intersections. This permits the TMC to obtain an up-to-date vision of the VANET's V2V connectivity status at every instant. However, the use of separate *DCUs* to upload the DiRCoD information of distinct road segments might imply a higher number of cellular transmissions.

From an implementation point of view, the FP mechanism operates as follows. Upon receiving a beacon including a CF_{ij} at road intersection I_i, vehicles that are placed near the center of the intersection activate a timer whose expiration activates the *DCU* upload. The duration of this timer is directly proportional to their distance from the center of I_i. Hence, the closest vehicle to the center of I_i uploads the *DCU* first. To prevent the other vehicles in the VANET from uploading the same *DCU*, the uploader includes an uploading field *UF* in its standard beacon message. This *UF* univocally indicates the road segment over which the uploaded VD_{ij} has been measured ($I_i \rightarrow I_j$). By overhearing the *UF*, vehicles that are participating in the uploading contention process abort their upload attempt. Moreover, upon receiving an *UF*, all the vehicles activate a road segment-specific uploading timer of *CF generation period* seconds. When a vehicle crosses I_i, it checks if it has the uploading timer for road segment $I_i \rightarrow I_j$ active. If it is not the case, the FP mechanism considers that no *DCU* for the road $I_i \rightarrow I_j$ has been uploaded in the last *CF* *generation period* seconds. The vehicle uploads then a *DCU* containing a VD_{ij} equal to VD_{ijmax}. Since the vehicle checks if the uploading timer is active also for the rest of the adjacent road segments of I_i, the uploaded *DCU* will contain in this case as many VD_{ij} as needed.

7.3.2 Global V2V connectivity context generation

RoAHD aims at detecting road segments with high multi-hop road Connectivity Stability (CS) over time (tens of seconds in this study). Multi-hop CS can in fact return indications on the possibility that a road segment will still be multi-hop connected in the next instants based on the fact that it has been connected during a previous period. This is very important since message injections from the TMC into the VANET can be performed after a given time compared to when the connectivity information is uploaded. Moreover, in most cases, a road providing high CS indirectly indicates a high presence of vehicles. Hence, this information can be exploited by injection strategies to inject messages over roads that can help the V2V dissemination to reach large sets of recipient nodes. In a generic way, injection strategies for a hybrid V2X dissemination scheme can be defined as procedures aimed at selecting a "strategic" combination V^n of n injection vehicles that is expected to optimize the performance of the V2V dissemination. The objective of such dissemination is to reach the highest number of recipient vehicles over a target area. The context characterization achieved in terms of connectivity stability is used by RoAHD to derive the "*Coverage Level*" $CL(V^n)$, an indicator of the expected amount of vehicles that would be reached after injecting message copies on a combination of vehicles V^n. As a result, the higher the CL, the more effective the injection process will be.

The TMC runs a connectivity processing scheme to derive the connectivity stability of all the road segments in the target area from the information included in the *DCUs* collected at different instants and from different intersections. The connectivity processing scheme exploits this information to calculate a global V2V connectivity map, and estimate the expected coverage level that drives its message injection strategies.

7.3.2.1 Connectivity Stability computation

The connectivity processing scheme running at the TMC computes connectivity stability values $CS_{VDij}(t)$ as an estimation of the percentage of time in which the road segment $I_i \rightarrow I_j$ experiences a specific virtual distance $VD_{ij}=\underline{VD}$ over a given time observation window. Connectivity stability values $CS_{VDij}(t)$ are computed for all the possible discrete values $\underline{VD}$ in the interval [0, 1,…, (VD_{ijmax}+1)] that road segment $I_i \rightarrow I_j$ can experience. According to the definitions of Section 7.3.1, VD_{ij}=0 indicates that the road experiences a full multi-hop road connectivity status. On the contrary $0<VD_{ij}<VD_{ijmax}$ indicates a partial connectivity status. $VD_{ij}= VD_{ijmax}+1$ (e.g. 5 for the road segment depicted in Figure 7-7) indicates a status of "*absence of connectivity*", that is a situation in which there is no vehicle at intersection I_i to upload a *DCU*.

The connectivity stability values are computed and updated at regular time steps of 1s based on VD_{ij} values contained in collected *DCUs*. Taking as reference Figure 7-5, let us consider that vehicle C uploads at instant *t* a *DCU* containing VD_{15}=0 (full connectivity over road $I_1 \rightarrow I_5$). The processing scheme expects receiving *DCUs* from vehicles at intersection I_1 at regular intervals of T_{update} seconds. T_{update} depends on the scheme adopted to collect road connectivity information. If IB is used, the processing scheme expects updates every $T_{update}=T_U$ seconds. On the contrary, when using FP, updates are expected with a period of T_{update}=*CF generation period* seconds. The processing scheme assigns to the road segment $I_1 \rightarrow I_5$ the received VD_{15}=0 for at most the next T_{update} time steps. If a new *DCU* is received by T_{update} seconds from the last update, the processing scheme starts assigning the new VD_{15}. Otherwise, the connectivity processing scheme considers that $I_1 \rightarrow I_5$ has become disconnected, and starts assigning the road segment a default value of $VD_{15max}+1$ until a new connectivity update is received. To compute the connectivity stability values $CS_{VD15}(t)$, the processing scheme considers the values of VD_{15} assigned to $I_1 \rightarrow I_5$ in the last T_{CS} time steps. More formally, in the case of a generic road segment $I_i \rightarrow I_j$, the connectivity stability $CS_{VDij}(t)$ of a given connectivity status $VD_{ij}=\underline{VD}$ is computed as:

$$CS_{VDij}(t) = \frac{card\{VD_{ij} = \underline{VD}\}(t)}{T_{CS}} \tag{7-1}$$

$CS_{VDij}(t)$ is then the ratio between the number of time steps in which $VD_{ij}=\underline{VD}$ over the last T_{CS} time steps, and the duration of T_{CS} in time steps. $CS_{VDij}(t)$ has then values in the interval [0, 1], with 1 indicating the maximum achievable connectivity stability. In order to provide $CS_{VDij}(t)$ with a statistical relevance, T_{CS} has to be adequately larger than the T_{update} period during which the connectivity status of a road segment is assigned a given $VD_{ij}=\underline{VD}$. When using the IB road connectivity uploading scheme, T_{update} is set as the adopted uploading timer duration T_U. This duration may be set to relatively high values (e.g. 15s in this study). In this case, consecutive *DCU* messages are received at the TMC with this periodicity. To ensure that T_{CS} is adequately larger than T_{update} even in these cases, the considered T_{CS} is set to 90s in this study.

7.3.2.2 Coverage Level estimation

The V2V context characterization described in the previous section is based on the expected stability of multi-hop road connectivity statuses $VD_{ij}=\underline{VD}$ measured by vehicles at all the road intersections I_i of a given area. The connectivity stability is used by the TMC's connectivity processing scheme to compute the coverage level $CL_i(t)$ of every intersection I_i. $CL_i(t)$ indirectly reflects the amount of vehicles that could be reached by V2V communications if a message copy was injected at intersection I_i. A higher amount of vehicles is expected to be reached injecting on vehicles placed at intersections having higher coverage levels.

The $CL_i(t)$ at intersection I_i is computed as the sum of the coverage levels $CL_{ij}(t)$ of every adjacent road segment $I_i \rightarrow I_j$ of I_i. For a generic road segment $I_i \rightarrow I_j$, $CL_{ij}(t)$ can be assigned values in the interval [0, (VD_{ijmax}+1)]. (VD_{ijmax}+1) indicates the maximum coverage level achievable, which in turn reflects a high amount of recipient vehicles on the road segment. A graphical representation of the coverage level computation for an intersection I_1 is depicted in Figure 7-8.

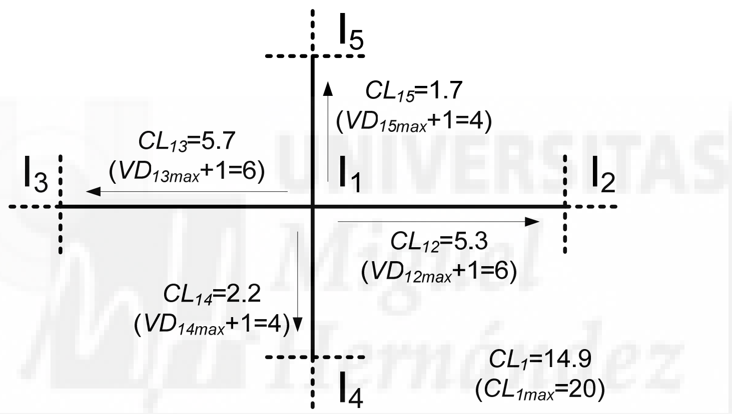


Figure 7-8. Example of CL computation for an intersection I_1.

For the computation of the $CL_{ij}(t)$ of a given road segment, some further definitions are needed. A road segment $I_i \rightarrow I_j$ instantaneously holds a "*Coverage Range*" $C_{ij}(t)$ defined as the complement of the $VD_{ij}(t)$ assigned by the connectivity processing scheme:

$$C_{ij}(t) = (VD_{ij\max} + 1) - VD_{ij}(t) \tag{7-2}$$

According to equation (7-2), the lower the instantaneous $VD_{ij}(t)$, the higher the coverage range $C_{ij}(t)$ of the road segment. Let c_{VDij} indicate the coverage range associated to a given value $VD_{ij}=\underline{VD}$ among those that can be assigned a road segment $I_i \rightarrow I_j$. The road segment depicted in Figure 7-7 has (VD_{ijmax}+1)=5. Therefore, the coverage range associated to VD_{ij}=0 is c_0=5; the coverage range associated to VD_{12}=1 is c_1=4, and so on. In this context, an association exists between VD_{ij}, c_{VDij}, and CS_{VDij}, for any of the $\underline{VD}$ that can be assigned to road $I_i \rightarrow I_j$. With these definitions, the instantaneous coverage level

$CL_{ij}(t)$ is computed by the connectivity processing scheme as a weighted average of all the possible coverage ranges c_{VDij} that the road segment $I_i \rightarrow I_j$ can be assigned:

$$CL_{ij}(t) = \frac{1}{\sum_{VD_{ij}=0}^{VD_{ij\max}+1} w_{VDij}(t) CS_{VDij}(t)} \sum_{VD_{ij}=0}^{VD_{ij\max}+1} w_{VDij}(t) CS_{VDij}(t) c_{VDij} \qquad (7\text{-}3)$$

The $CL_{ij}(t)$ assumes then values in the interval [0, (VD_{ijmax}+1)]. In equation (7-3), each coverage range c_{VDij} is weighted by the currently experienced connectivity stability value $CS_{VDij}(t)$ associated to $VD_{ij}=\underline{VD}$. The computed $CL_{ij}(t)$ is higher when the road shows higher stability for lower values of $VD_{ij}=\underline{VD}$, given that lower $\underline{VD}$ values are associated to higher coverage ranges. Higher coverage ranges indicate the capability of the road segment to support multi-hop transmissions over larger portions of its length. Higher connectivity stabilities associated to these ranges indicate that this capability is not occasional, but on the contrary is ensured by a high presence of vehicles. Since the CS_{VDij} values are calculated over a moderately long observation window (as specified in Section 7.3.2.1, T_{CS} is set to 90s in this work), they do not adapt rapidly to changes of the connectivity status of a road segment. As a consequence, instantaneous $CS_{VDij}(t)$ values might not perfectly represent current road connectivity and coverage capabilities. To cope with this issue while preserving the statistical relevance achieved from connectivity stability values, the $CL_{ij}(t)$ calculation (7-3) also includes the weights $w_{VDij}(t)$. The $w_{VDij}(t)$ are used to weight the $CS_{VDij}(t)$ according to the time $T_{\underline{VD}}(t)$ passed from when the connectivity processing scheme last assigned the value $VD_{ij}=\underline{VD}$ to the road segment. The weigths $w_{VDij}(t)$ have continuous values in the interval [0, 1] and are built to exponentially decay as $T_{\underline{VD}}(t)$ increases:

$$w_{VDij}(t) = a^{T_{\underline{VD}}(t)} \qquad (7\text{-}4)$$

The constant a in equation (7-4) is set to a value that generates $w_{VDij}(t)$=0.1 when $T_{\underline{VD}}(t)$=20s. As a result, connectivity stabilities $CS_{VDij}(t)$ associated to $\underline{VD}$ values that have not been recently assigned to the road segment have less influence in the CL_{ij} calculation.

Figure 7-9 represents in the lower graph the simulated time variation of $CL_{ij}(t)$ over a given road segment having (VD_{ijmax}+1)=5. $CL_{ij}(t)$ results from the $VD_{ij}(t)$ and $CS_{VDij}(t)$ trends depicted in the upper graphs. As the figure shows in the second part of the simulated time frame, $CL_{ij}(t)$ is higher when the road has higher CS_{VDij} for lower values $\underline{VD}$ of VD_{ij} (e.g. VD_{ij}=0), and when such values have been recently assigned to the road by the connectivity processing scheme. The effect of the weigths $w_{VDij}(t)$ is visible directly before t=400s. In this period, the connectivity processing scheme is assigning higher VD values (VD_{ij}=4 and VD_{ij}=5). As a result, the computed instantaneous $CL_{ij}(t)$ decreases, even if the connectivity stability of VD_{ij}=0 is currently higher than all the other CS_{VDij} connectivity stability values.

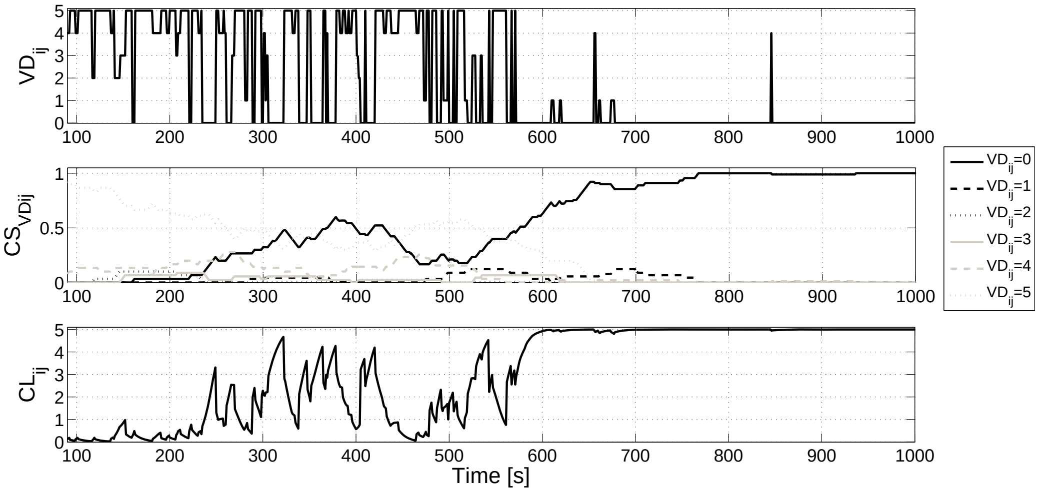


Figure 7-9. Example of CL computation for a road segment $I_i \rightarrow I_j$.

7.3.3 Message injection strategies

The RoAHD V2X hybrid dissemination mechanism aims at reducing the cellular energy and channel cost by using the cellular network to inject only a limited number $\underline{n}$ of message copies. RoAHD's injection strategies are then aimed at identifying the combination of $\underline{n}$ injection vehicles that maximize the overall coverage level $CL(V^{\underline{n}})$ over the targeted relevance area. To select the combination $V^{\underline{n}}$ maximizing the overall $CL(V^{\underline{n}})$, the TMC's connectivity processing scheme updates, at every time step, the expected coverage level $CL_i(t)$ of every intersection I_i in the relevance area. If a road segment $I_i \rightarrow I_j$ holds an adequately high coverage level, then a message copy injected at I_i can be multi-hop disseminated towards I_j, and from I_j over the road segments adjacent to this intersection. The connectivity processing scheme can analyze the coverage level $CL_i(t)$ of every intersection I_i to compute "*Connected Sets of Intersections*" (CSIs) over the relevance area. In the scenario depicted in Figure 7-4, the TMC would detect two CSIs: one formed by the intersections I_7, I_8, I_3, and I_9, and another one composed by the intersections I_1, and I_5. Injecting one message over any of the intersections composing a CSI would be enough to reliably disseminate the message over all the road segments of the connected set by V2V communications. This study defines that two intersections I_i and I_j form a CSI at instant *t* if the road segment between them has a CL higher than a given threshold over both its directions:

$$CL_{ij}(t) \geq Thr \cap CL_{ji}(t) \geq Thr \tag{7-5}$$

The threshold *Thr* considered in this work is 80% of the maximum $CL_{ij}(t)$ that a road segment $I_i \rightarrow I_j$ can be assigned, i.e. $VD_{ijmax}+1$. Considering a lower threshold would not ensure the actual capability of $I_i \rightarrow I_j$ to safely relay injected messages over the road segment. On the contrary, higher thresholds might pose too strict requirements to the formation of CSIs, and could subestimate the multi-hop forwarding properties of road segments.

Figure 7-10 depicts two intersections I_1 and I_2 forming a CSI. Injecting a message copy on a CSI is expected to ensure a coverage level CL_{CSI} equal to the sum of the CL_i provided by the intersections composing the connected set.

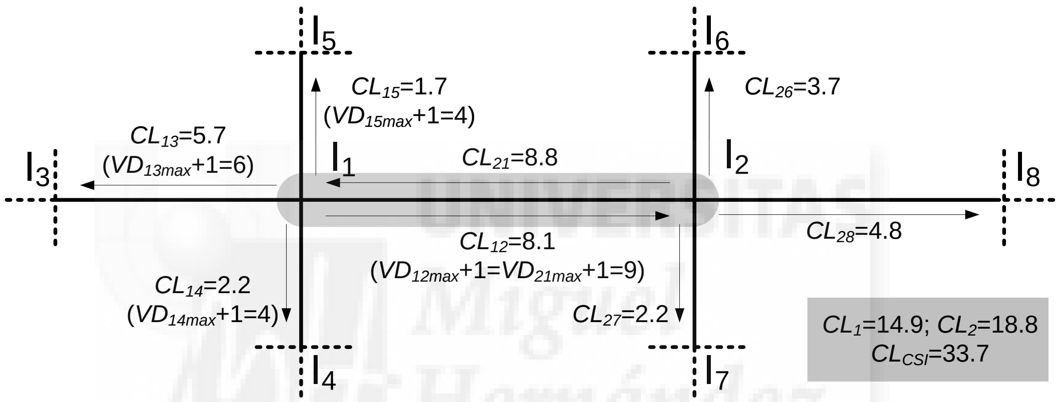


Figure 7-10. Example of CL computation for a connected set of intersections.

When a message injection has to be executed, the connectivity processing scheme computes connected sets of intersections CSI_i in the relevance area, and calculates their expected coverage level CL_{CSIi}. Intersections not belonging to any CSI_i are considered as CSIs of size equal to 1. To obtain the highest levels of message reception in the VANET, the $\underline{n}$ available message copies are injected in the CSIs that are expected to ensure the highest coverage levels. Injections are performed according to the injection strategies that are next defined.

7.3.3.1 Injections with unacknowledged injection vehicle positions

The connectivity processing scheme analyzes the computed coverage levels to inject the available $\underline{n}$ message copies in the $\underline{n}$ CSIs with the highest expected CL_{CSIi}. On a given CSI_i, the copy is injected on a vehicle placed at the intersection I_i providing the highest CL_i. According to the coverage level definitions of Section 7.3.2.2, I_i is adjacent to road segments expected to host the highest number of vehicles that could receive the injected message using V2V communications. The vehicle that receives the injected message at I_i is the one that last uploaded a *DCU* for this intersection. As this vehicles does not inform the TMC about its actual position at the time of the injection, these injections are referred to as "*injections with unacknowledged injection vehicle positions*".

As expected, the computation of the connected sets of intersection CSI_i, the resulting CL_{CSIi}, and the associated injection vehicles is influenced by the adopted road connectivity information collection scheme. An injection strategy based on a V2V connectivity characterization achieved with the IB uploading scheme is referred to as "*Injection with Intersection-based Road Connectivity Characterization (IBRCC) Awareness*". On the contrary, an injection strategy based on a characterization deriving from the use of the FP uploading mechanism is referred to as "*Injection with Fast Probing Road Connectivity Characterization (FPRCC) Awareness*".

7.3.3.2 Injections with acknowledged injection vehicle positions

In the previous set of injection strategies, a message copy is injected on the vehicle that last uploaded a *DCU* for a given intersection I_i. In this case, there is no guarantee that the injection vehicle is still placed at I_i at the moment of the injection. In a very unfortunate scenario, the injection vehicle might be already out of the selected CSI and not in adequate conditions to reliably forward the injected message to the rest of vehicles. This might be the case when the adopted road connectivity collection mechanism uploads *DCUs* with moderately low frequency. An example of such collection mechanism is an IB uploading scheme adopting an uploading timer duration T_U equal or higher than 10s.

To overcome the possible negative effects on the V2X dissemination performance, RoAHD proposes the following solution. Before injecting the $\underline{n}$ message copies, the TMC "announces" the injection with a small broadcast "*Injection Announcement Message*" (*IAM*) through a downlink cellular channel. Upon receiving the *IAM* message, the vehicles placed at road intersections activate a distributed process to select the most appropriate injection vehicles. One injection vehicle per intersection is selected. The selected vehicles "acknowledge" their presence at the intersection, and availability to receive the injected message, by uploading a cellular uplink message containing their GPS position. In UMTS, the injection could be announced efficiently using the Multimedia Broadcast Multicast Service (MBMS) [167]. As demonstrated in [168] and [169], a non-stop MBMS service avoiding connection setup delays can be executed over geo-defined parts of a UMTS cell with latencies lower than 1 second. When receiving an *IAM* at an intersection, a vehicle activates a timer whose expiration triggers the upload of its GPS position. The duration of the timer is directly proportional to the vehicle's distance from the center of the intersection. As a result, the first uploader is the vehicle occupying the most centric position in the intersection zone, and hence also the most suited to start the V2V dissemination of an injected message. To abort the uploading attempt on the other vehicles of the intersection, the uploader includes a specific flag in its next standard beacon. By overhearing this flag, receiving vehicles having the timer active abort their upload attempt.

RoAHD improves the IBRCC and FPRCC injection strategies (Section 7.3.3.1) with the described mechanism to acknowledge the position of injection vehicles. The available $\underline{n}$ message copies are injected in the $\underline{n}$ CSIs providing the highest CL_{CSIi}. On a given CSI_i, the copy is still injected on the intersection I_i providing the highest CL_i. However, differently from the basic IBRCC and FPRCC strategies, in this case the vehicle that receives the injected message is the one that acknowledged its position at the intersection before the injection. In the following, these strategies are referred to as "*Injections with IBRCC (or FPRCC) and acknowledged injection vehicle positions (AP)*". These strategies are indicated with "IBRCC-AP" and "FPRCC-AP", respectively.

7.3.3.3 Centric and multiple injections

Uploading *DCU* messages with lower frequency can provide the non-negligible advantage of consuming less cellular channel resources. This might be achieved by the IB road connectivity uploading scheme using relatively high values of its T_U parameter (Section 7.3.1.1). However, not uploading the road connectivity information very frequently might degrade the accuracy of the global VANET's connectivity characterization. Injection strategies based on characterizations that are not updated very frequently might inject on CSIs not as connected as expected, or on intersections not actually providing the expected coverage levels and possibly disconnected from the rest of their CSIs. In this context, RoAHD proposes variants of the previously defined injection strategies to reduce the impact of lower characterization accuracies obtained at a lower cellular channel cost. These variants use "centric" and "multiple" injections over CSIs. Injecting a message copy on an intersection occupying a more centric position in a CSI increases the probability for the message to be disseminated towards peripheral intersections. In addition, it also better handles situations in which the considered CSI is actually partitioned in subsets of connected intersections. The injection strategy variants proposed by RoAHD work as follow. Let us consider a given CSI formed by various intersections. According to the definition of the previously presented strategies, only one message should be injected on the CSI. Instead of injecting this message on the intersection I_i having the highest coverage level CL_i, the first variant injects the message on the intersection having the most centric position on the CSI. The most centric intersection is the intersection having the shorter distance from the other intersections of the connected set. An injection strategy using this variant will be referred to as "*injection strategy with centric injections*" (e.g. "IBRCC-AP with centric injections"). The second variant considers the possibility of injecting multiple message copies over a CSI to better face the effects of possible V2V disconnections in CSIs of relatively large size. In this context, RoAHD defines the number *m* of messages to inject on a CSI as a function of its size $size_{CSI}$.

$$m = \left\lfloor \frac{size_{CSI}}{s} \right\rfloor + 1 \qquad (7\text{-}6)$$

With respect to the original configuration in which only one message is injected in the CSI, this variant injects as many additional messages as the size of the CSI equals multiples of s (e.g. with s=5, if $size_{CSI}$=3 then m=1; if $size_{CSI}$=7, then m=2; if $size_{CSI}$=11, then m=3, and so on). s is a protocol parameter that can be set to lower values to perform more injections on a CSI, thereby increasing the V2V dissemination robustness. In a given CSI, injections are performed on the combination of m intersections occupying the most centric positions. An injection strategy using this variant is referred to as "*injection strategy with multiple injections*" (e.g. "IBRCC-AP with multiple injections").

To compute the centrality of intersections (or combinations of m intersections), RoAHD considers graph theory, and handles a CSI as an undirected graph in which nodes represent the intersections and edges represent the road sections between them. Edges are associated weights representing the distance between two adjacent intersections in units of DiRCoD's road sections (e.g. in Figure 7-7, this distance is VD_{ijmax}=4). An example of planar graph associated to a CSI composed by 7 intersections is depicted in Figure 7-11. Using the well known Dijkstra algorithm, it is possible to compute the shortest distance $d(I_i,I_j)$ separating any two intersections I_i and I_j. In this context, the most centric intersection is calculated as the intersection having the shortest average distance from the other intersections of the CSI. In the example of Figure 7-11, the intersection I_2 is separated by the rest of the intersections by the distances $d(I_2,I_1)=3$, $d(I_2,I_3)=2$, $d(I_2,I_4)=2$, $d(I_2,I_5)=4$, $d(I_2,I_6)=5$, and $d(I_2,I_7)=7$. As a result, the average distance separating I_2 from the other intersections is 3.83. Since no other intersection has a shorter average distance, intersection I_2 is considered the most centric intersection of the CSI.

If m message copies have to be injected in the CSI, all the possible combinations of m intersections are analyzed to derive the most centric one. To compute the centrality of a given combination, the following definitions are needed. Let us consider a specific combination of m intersections out of the $size_{CSI}$ intersections forming the CSI. For the ($size_{CSI} - m$) intersections not belonging to the combination, the distance $d_{closest}$ is computed. $d_{closest}$ is defined as the shortest distance to any of the intersections belonging to the considered combination. In the example of Figure 7-11, if the combination of m=2 intersections (I_2, I_5) is considered, $d_{closest}$ has to be computed for the intersections I_1, I_3, I_4,

I_6, and I_7. For the intersection I_1, $d_{closest}$ is the minimum value between $d(I_1,I_2)$ and $d(I_1,I_5)$. As a result, $d_{closest}$ is $d(I_1,I_2)=3$ for this intersection. The other $d_{closest}$ values are $d(I_3,I_2)=2$, $d(I_4,I_2)=2$, $d(I_6,I_5)=1$, and $d(I_7,I_5)=3$. A set of distances $d_{closest}$ is associated to each possible combination of *m* intersections. In this context, the most centric combination of *m* intersections is computed as the one minimizing the average $d_{closest}$ in the CSI. In the example of Figure 7-11, if the combination (I_2, I_5) is considered, the average $d_{closest}$ is calculated with the above listed values and is equal to 2.2. Since this value is not minimized by any other combination, then (I_2, I_5) is considered the most centric combination of 2 intersections.

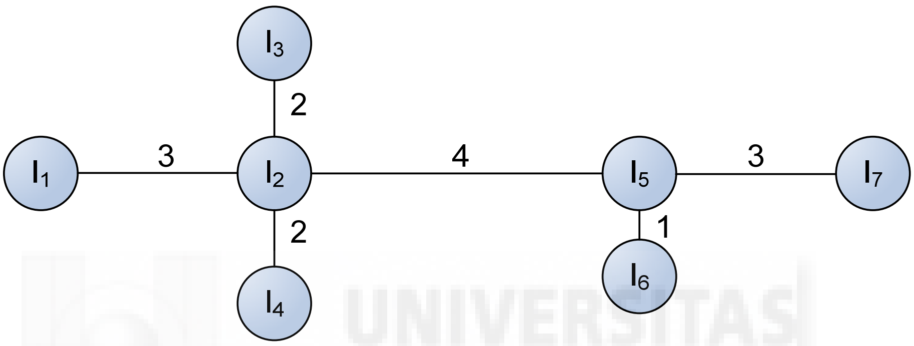


Figure 7-11. Planar graph representation of a CSI.

7.3.4 V2V dissemination

Injecting message copies at road intersections optimizes the V2V dissemination within a VANET. This is the case because vehicles at road intersections can use V2V communications in LOS propagation conditions to simultaneously reach vehicles located over adjacent road segments. To disseminate the injected copies, RoAHD defines a V2V dissemination mechanism called Road Topology-Aware Contention-based Broadcasting (TOPOCBB). TOPOCBB is a GeoBroadcast protocol that disseminates the message using multi-hop broadcast transmissions. To avoid flooding the VANET, such transmissions are done by only a limited set of vehicles. As depicted in Figure 7-13, these vehicles are distributedly selected based on their capability to extend the V2V dissemination towards road intersections that have not yet been reached. To this aim, TOPOCBB implements a distributed contention-based algorithm similar to that used by TOPOCBF (Section 6.3.3). TOPOCBB inserts an injected message copy to disseminate in the payload of a standard GeoNetworking packet used for GeoBroadcast transmissions [33]. The GeoNetworking header of this packet contains the location of the current sender vehicle, as well as the coordinates (both center and sprawl) of the relevance area (Section 2.5.2). Vehicles receiving the packet out of the relevance area will not process or broadcast the received message. To apply the TOPOCBB's contention-based broadcasting approach towards an unaddressed intersection, the geographical coordinates of this intersection are added in the packet. These coordinates are included in the GeoNetworking header using an additional "*Next Intersection Field" (NIF).* The resulting format of a TOPOCBB packet is depicted in Figure 7-12. The *NIF* indicates the intersection towards which the message has to be broadcasted.

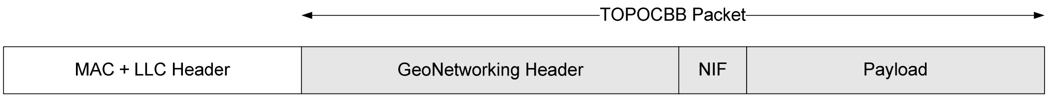


Figure 7-12. Structure of a TOPOCBB packet.

To explain how TOPOCBB selects its broadcasters, let us consider the scenario depicted in Figure 7-13. Vehicle A receives the injected message copy through a cellular link in the intersection I_3 selected by the connectivity processing scheme. Vehicle A includes this message in the payload of a TOPOCBB packet and broadcasts it with a *NIF* indicating the injection intersection I_3. All the vehicles store a list of the already addressed intersections. This list is updated every time a TOPOCBB packet is received. A vehicle receiving a TOPOCBB packet analyzes its current geographical location and the location of the sender to check whether it provides progress towards the intersection indicated in the *NIF* (the progress is computed following equation (6-4)). If it is the case and the intersection was not addressed previously, the receiver activates a timer specific for this intersection. The duration of the timer is inversely proportional to the progress towards the intersection. The duration of this timer is computed following equation (6-3). The timer's expiration triggers the broadcast transmission of the received message. The vehicle that provides the highest progress is the first to broadcast the received message. By overhearing the broadcasted message, the other vehicles with the timer active for the intersection indicated in the *NIF* abort their broadcast attempt.

Following the example illustrated in Figure 7-13, let us suppose that the message broadcasted by A with *NIF*=I_3 is received by all the vehicles up to vehicles C, B, and D. None of these vehicles activates a timer to broadcast the received message towards intersection I_3 given that none of them provide progress towards this intersection. If a vehicle that receives the message does not provide progress towards the intersection indicated in the *NIF*, it checks whether it provides progress towards another intersection. If the vehicle is placed on a road segment, it checks the other intersection delimiting the road segment. Otherwise, if the vehicle is located at an intersection, it checks the adjacent intersections. If the receiving vehicle provides progress towards one of these intersections, and if the intersection was not addressed previously, it activates a new timer to broadcast the received message towards such intersection. The duration of the timer is inversely proportional to the progress provided towards the sought intersection. The vehicle with the shorter timer changes the *NIF* in the TOPOCBB packet to adress the new intersection, and broadcasts the received message towards this intersection. The other vehicles abort their broadasting attempt upon overhearing this transmission. In the scenario depicted in Figure 7-13, only vehicles C, B and D broadcast the message received from vehicle A. They broadcast towards intersection I_1, I_4, and I_5, respectively. In fact they indicate such intersections in the *NIF* before broadcasting. Let us now suppose that the message broadcasted by vehicle C with *NIF*=I_1 is received by vehicles A, H, and G. Since vehicle G is the closest one to I_1, it broadcasts the message first without changing the *NIF*. Vehicles A and H do not activate a timer to broadcast the message towards I_1 since they do not provide any progress towards I_1. In addition, they do not activate a timer to broadcast the message towards I_3 since they already received a message addressed to I_3. The message broadcasted by vehicle G with *NIF*= I_1 is further broadcasted by vehicle F towards I_2. The message broadcasted by vehicle D with *NIF*=I_5 is not received by any closer vehicle to I_5 than D itself. The receiving vehicles placed over the road segment I_5-I_6, activate a timer to broadcast the message towards I_6. In this case, vehicle E results the first and only broadcaster. This process is repeated until all the receiving vehicles have no adjacent intersection to address. In this way, TOPOCBB ensures to the maximum possible extent a full dissemination of the injected messages over the connected sets of intersections present on the relevance area.

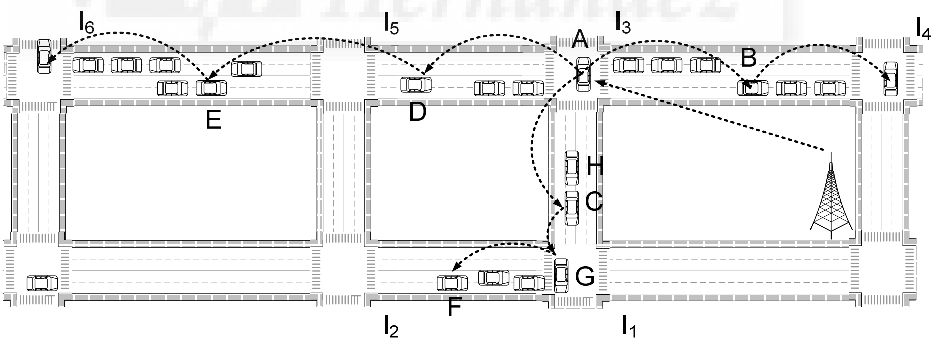


Figure 7-13. TOPOCBB selection of relay vehicles.

7.4 Benchmark hybrid V2X dissemination schemes

The performance and efficiency of RoAHD is compared against that obtained with other hybrid V2X dissemination schemes. To ensure a fair comparison, these schemes inject the same fixed number $\underline{n}$ of message copies in the VANET, and also employ

TOPOCBB for the V2V dissemination. The schemes differ on the V2V connectivity characterization used to make injection decisions:

- *GPS injection strategy.* A centralized V2V connectivity characterization of the VANET can be obtained at the TMC by combining the GPS position that each vehicle in the relevance uploads with a regular period *p* [91][162]. This study considers that the TMC analyzes the uploaded GPS positions to derive Connected Sets of Vehicles (CSVs) in the VANET. CSVs are defined as sets of vehicles that can communicate with either direct or multi-hop transmissions. Injecting a message copy over a CSV permits its V2V dissemination to all the vehicles of the connected set. To identify the CSVs, the TMC considers that two vehicles can directly communicate if they are separated by less than a given inter-vehicle distance *r*. This simplified model also considers the shielding effect of large-sized obstacles to radio propagation. This effect is taken into account by preventing communications between vehicles driving on roads separated by buildings. For this purpose, it is considered that the TMC holds a digital map of the buildings in the relevance area. The GPS injection strategy injects the $\underline{n}$ available message copies in the $\underline{n}$ CSVs having the highest number of vehicles. Within a CSV, the message is injected on the vehicle having the shortest average distance to the other vehicles of its CSV. Considering different values of the uploading period *p* and the inter-vehicle distance *r* influences the calculation of CSVs and may result in distinct delivery performance levels.

- *Idealistic injection strategy.* This injection strategy assumes that the TMC knows the actual location of all vehicles at any time. As a result, the TMC is considered to hold an "idealistic" VANET's V2V connectivity characterization that is only achievable through simulations. At the moment of injecting, the TMC retrieves the current vehicle positions from the adopted simulation environment. It then computes CSVs and injection vehicles following the previously described principles. Due to its nature, this injection strategy is expected to adopt a more precise V2V connectivity characterization, and hence is used as an idealistic benchmark to compare the performance of the other injection schemes.

- *Random injection strategy.* This injection strategy does not use any VANET connectivity characterization. The $\underline{n}$ available message copies are injected by the TMC on $\underline{n}$ randomly selected vehicles. This strategy permits quantifying the added value that using a V2V connectivity characterization provides to the dissemination process.

7.5 Performance evaluation

The evaluation of RoAHD is done in two steps. In the first one, the V2V connectivity context characterization retrieved by the IB connectivity information uploading scheme is compared with that obtained by the reference FP scheme. This first analysis considers increasing values of the IB's uploading timer duration T_U, and investigates to what extent saving cellular uplink resources by collecting less connectivity information can affect the accuracy of the resulting context characterization. In this way, the results of this investigation return first theoretical insights about the usefulness of the IB uploading mechanism for increasing degrees of its channel efficiency. In the second step, the connectivity context characterizations obtained from the first analysis are used to drive the centralized message injection strategies defined in Section 7.3.3. The performance of these strategies is compared against that obtained by the injection strategies defined in Section 7.4. This second step investigates the impact of the V2V connectivity context characterization obtained with lower channel cost on the effectiveness of injection strategies.

7.5.1 Simulation scenario

The performance of RoAHD has been evaluated through simulations on the complete iTETRIS simulation platform. The iTETRIS architecture permits implementing the various functional blocks composing RoAHD's operation (Figure 7-6) in a very modular way. The adopted implementation and simulation scheme is shown in Figure 7-14. SUMO simulates the vehicular mobility and regularly provides the rest of the iTETRIS' blocks with updates of the location of each vehicle. DiRCoD's transmissions, *DCU* and GPS position uploads, as well as the TOPOCBB dissemination protocol are all simulated in ns-3. The TCM connectivity processing and message injection decisions are implemented in the iAPP block of iTETRIS. When ns-3 notifies the iAPP about the reception of *DCUs* or GPS position uploads, the connectivity processing scheme updates the VANET's V2V connectivity context. When a message has to be disseminated, the processing scheme executes an injection strategy. Once the injection vehicles have been determined, the processing scheme triggers the simulation of message injections in ns-3. After simulating the wireless transmissions resulting from these injections (UMTS downlink unicast transmissions followed by TOPOCBB V2V dissemination), ns-3 analyzes if the vehicles in the relevance area have correctly received the messages to determine the V2X dissemination performance.

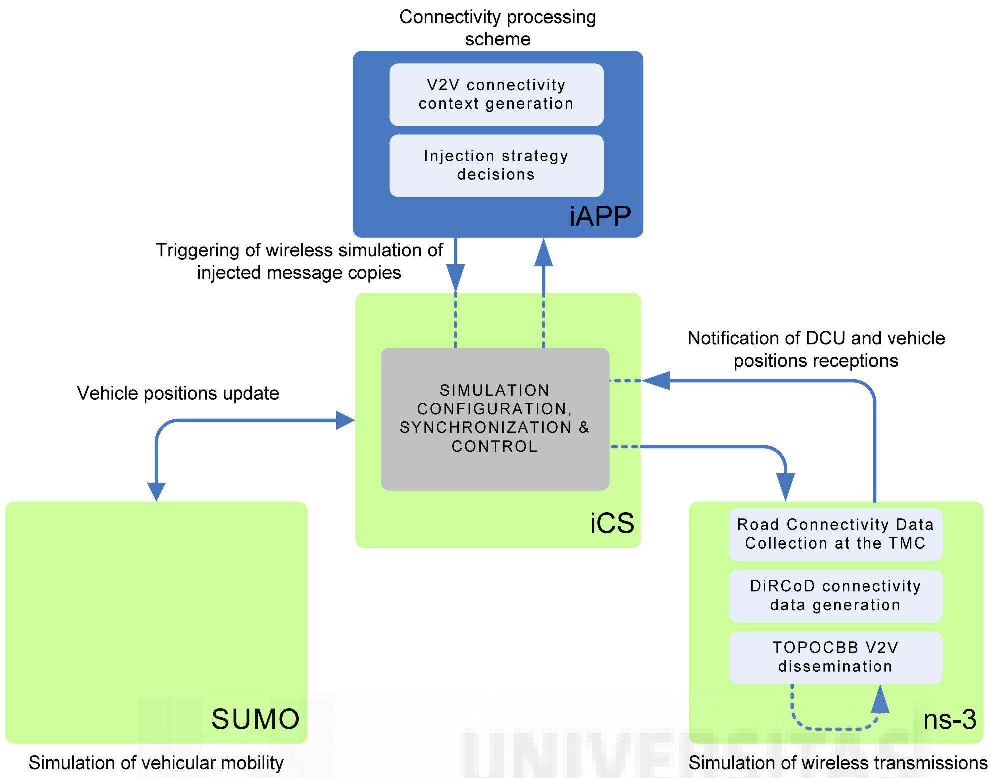


Figure 7-14. Implementation and simulation of RoAHD in iTETRIS.

Without any loss of generality, the road network scenario adopted as relevance area in the simulations is a Manhattan-like grid of 2.5*2.25 km (Figure 7-15). The grid is composed by 56 intersections and 97 road segments with different lengths ranging from 200m to 450m. The vehicles have a maximum allowed speed of 50 km/h. The traffic flows along the road segments are bidirectional; no intersection is managed by traffic lights. Three different vehicular traffic scenarios have been considered. In each of these scenarios, time and space variations of the vehicular flows are imposed over the Manhattan grid in order to reproduce changes in the overall V2V connectivity status. Distinct sets of road segments (like those labelled with “zone 1” and “zone 2” in Figure 7-15) have then different vehicular densities that vary during the simulated time. The three scenarios have been categorized according to the minimum and maximum experienced vehicular density. The first simulated scenario (Scenario 1) is characterized by a vehicular density ranging from 3 to 15 vehicles/km/lane. The second scenario (Scenario 2) has a vehicular density ranging from 3 to 22 vehicles/km/lane. Finally, the third scenario (Scenario 3) has a vehicular density ranging from 3 to 30 vehicles/km/lane. As a result, a traffic scenario with a higher number corresponds to an overall higher vehicular density in the considered road network.

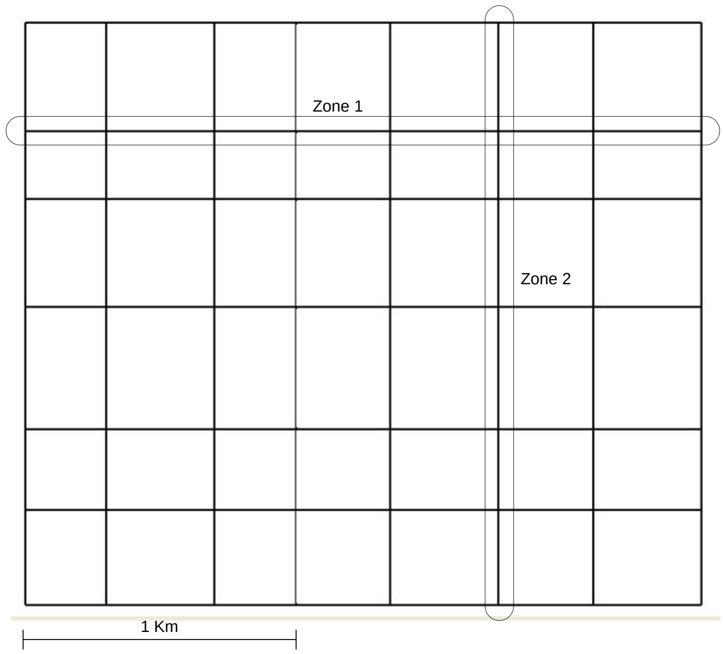


Figure 7-15. Manhattan-like road network scenario adopted for RoAHD's evaluation.

Every simulated vehicle is able to communicate using a UMTS User Equipment (UE) and a 5.9GHz ETSI ITS G5 radio interface. ITS G5 interfaces are considered to transmit beacon messages (issued at a 2Hz frequency) and TOPOCBB packets on the ITS G5 control channel (G5CC). These transmissions take place at the default 6Mbit/s data rate transmission mode of the standard [12], and with a transmission power of 20dBm. As explained in Section 5.2.2, the use of a transmission power of 20dBm in iTETRIS results in DiRCoD road sections with a length of 95m.

Section 5.5.1 explained how standard beacon messages can be extended to include DiRCoD connectivity fields. Similarly, beacons are extended with one additional byte to include the uploading fields (*UFs*) necessary for implementing the DiRCoD's information collection mechanisms outlined in Section 7.3.1. For the implementation of TOPOCBB, the GeoNetworking header of standard GeoBroadcast packets is extended with 8 bytes to code the *NIF*: 4 bytes are used to code the latitude, and 4 bytes are used to represent the longitude of the next intersection to address.

To support the collection of *DCUs*, vehicle GPS positions, and the injection of messages, a UMTS node B serving the whole considered area is deployed. The amount of information carried by a *DCU* uploaded at a generic intersection I_i is 8 bytes to code the intersection position, plus one byte to represent each virtual distance VD_{ij} measured over the adjacent road segment $I_i \rightarrow I_j$. 8 bytes are needed to upload vehicle GPS positions. Due to the small size of these messages, this work considers their transmission on the UMTS

Random Access Channel (RACH) mapped on the Physical RACH (PRACH). The RACH is a common uplink channel normally used for signaling purposes. Its adoption to upload small amounts of data can increase the number of simultaneous transmissions since users are not required to activate dedicated channels. The feasibility of frequent (e.g. every 10s) vehicular data uploading on the PRACH is studied in [163]. As the authors demonstrate, if the uploaded message is small (e.g. 20 bytes on 10 ms frames), more than 600 users per cell can be served. To calculate the overhead generated on the PRACH by the compared uploading schemes, this work considers transmitting uplink messages in 16 bytes Radio Link Control (RLC) payloads over frames of 10 ms. As described in [170], this transmission mode implies a user data rate of 12.8 kbps, and a total overhead (considering the additional overhead of the lower layers) of 48.5 bytes per uploaded message. For the IB uploading mechanism described in Section 7.3.1.1, four values of the uploading timer duration T_U are simulated: 2, 5, 10, and 15 seconds.

The UMTS node B injects $\underline{n}$ message copies of a message having a size of 300 bytes. For this purpose, dedicated channels with a user data rate of 128kbps are considered. The $\underline{n}$ message copies are injected periodically every 10s for an overall simulation period of 1000s. Three configurations are studied in which the UMTS node B injects $\underline{n}$=3, 5, and 7 message copies, respectively. The simulation results reported in the following provide an accuracy equivalent to relative errors below 0.05.

7.5.2 Performance metrics

The performance metrics adopted for RoAHD's evaluations are categorized based on the two evaluation steps described at the beginning of Section 7.5.

7.5.2.1 V2V Connectivity context characterization

The capability of the IB uploading mechanism to support the generation of the connectivity context characterization is done comparing the obtained coverage level values (CL^{IB}) to those achieved with FP (CL^{FP}). In this context, the following performance metrics are defined:

- *Instantaneous CL estimation error over a single road segment.* Considering a given road segment $I_i \rightarrow I_j$, this error is defined as the absolute value of the difference between the instantaneous coverage level calculated when the FP scheme is used, and that obtained when IB is adopted:

$$e_{CLij}(t) = \left| \frac{CL_{ij}^{FP}(t) - CL_{ij}^{CI}(t)}{VD_{ij\max} + 1} \right| \tag{7-7}$$

According to Section 7.3.2.2, road segments $I_i \rightarrow I_j$ with different lengths result in distinct maximum coverage levels (VD_{ijmax}+1). To compare the instantaneous error over roads with different lengths, the metric is normalized by the (VD_{ijmax} +1) value of the selected road segment. The resulting error has continuous values in the interval [0, 1], with 1 indicating the maximum error that can be observed.

- *Instantaneous average CL estimation error:* defined as the average of the $e_{CLij}(t)$ computed over all the road segments $I_i \rightarrow I_j$ of the relevance area (Figure 7-15):

$$\overline{e_{CLij}(t)} = \frac{1}{card\{I_i \rightarrow I_j\}} \sum_{I_i \rightarrow I_j} e_{CLij}(t) \tag{7-8}$$

where $card\{I_i \rightarrow I_j\}$ indicates the cardinality of the road segments forming the road network. Compared to the previous metric, this metric provides a larger scale measure of how IB can support the generation of a correct V2V connectivity context characterization.

- *Average CL estimation error:* defined as the temporal average of instantaneous average errors (7-8) calculated at regular time steps T of 1s during the complete simulated period:

$$\overline{\overline{e_{CLij}}} = \frac{1}{card\{i\}} \sum_{i} \overline{e_{CLij}(iT)} \tag{7-9}$$

where $card\{i\}$ represents the total number of time steps composing the simulated time period. Since this metric averages the estimation error over space and time, it is expected to return comprehensive indications about the accuracy of the V2V connectivity characterization

The coverage level estimation error can only return partial indications on the usefulness of the V2V connectivity context characterization obtained by the IB scheme. An injection strategy does not necessarily require that the CL_{ij} values obtained with IB perfectly match those obtained by FP. On the contrary, it needs a criterion to correctly distinguish different candidate road segments (or intersections) to determine where to inject messages. In this context, if the CL_{ij} values obtained by IB are well correlated with those obtained by the reference FP (the estimation error $e_{CLij}(t)$ is almost the same for all the road segments $I_i \rightarrow I_j$), then IB's connectivity characterization is expected to be as good as FP's in supporting effective injection decisions. To measure this correlation, the following metrics are defined:

- *Instantaneous statistical correlation between CL values obtained with IB, and with FP.* The set of $CL_{ij}(t)$ values obtained by IB at instant t for all the road segments $I_i \rightarrow I_j$

in the considered area is defined as CL^{IB}. Similarly, the set of $CL_{ij}(t)$ values obtained by FP are indicated as CL^{FP}. The statistical correlation between this two families of values at the instant *t* is computed using the Pearson's correlation coefficient:

$$\rho_{CL^{IB}CL^{FP}}(t) = \frac{\text{cov}(CL^{IB}, CL^{FP})}{\sigma_{CL^{IB}}\sigma_{CL^{FP}}} \tag{7-10}$$

that is the ratio between the covariance of the two considered families of values, and the product of the their standard deviations. The correlation coefficient (7-10) returns continuous values in the interval [-1, 1], with 1 indicating a perfect direct correlation, 0 indicating total absence of correlation, and -1 perfect inverse correlation. By analyzing instantaneous values of this indicator, it is possible to understand if correlation is maintained irrespectively of the changes in the VANET's V2V connectivity status.

- *Average statistical correlation between CL values obtained with IB, and with FP.* This metric is obtained averaging instantaneous values of the correlation coefficient (7-10) calculated at regular time steps *T* of 1s during the overall simulated period:

$$\overline{\rho_{CL^{IB}CL^{FP}}} = \frac{1}{card\{i\}}\sum_i \rho_{CL^{IB}CL^{FP}}(iT) \tag{7-11}$$

where *card{i}* indicates the total number of time steps composing the simulated period. This metric allows appreciating on average to what extent the V2V connectivity characterization obtained with IB correlates with that achieved by the reference FP.

In addition to measuring the quality of the V2V connectivity context characterization, it is also important to assess the communications overhead generated by RoAHD's multi-hop road connectivity collection mechanisms. This overhead is measured over both the cellular UMTS uplink channel, and the vehicular-ad hoc ITS G5 control channel using the following metrics:

- *Total communications overhead on the UMTS uplink channel:* represents the total communications overhead (in bytes) generated on the UMTS PRACH to upload *DCUs* with either IB or FP. It is referred to as "total" as it considers the overhead generated along the entire simulated period.
- *Total communications overhead on the ITS G5 control channel:* represents the total communications overhead (in bytes) generated on the ITS G5 control channel to implement either IB or FP. For the calculation of this overhead, the additional uploading field *UFs* that the schemes include in standard beacon messages every time

a *DCU* is uploaded (see Section 7.3.1) are considered. This overhead is referred to as "total" as it considers the overhead generated along the entire simulated period.

7.5.2.2 Message injection strategies

RoAHD's injection strategies are compared to those driven by V2V connectivity characterizations obtained using the position of vehicles (Section 7.4). This comparison is made considering the communications overhead required to generate the distinct V2V connectivity characterizations, the communications overhead needed to implement the injection strategies, and the V2X dissemination delivery performance. For this purpose, the following metrics are defined:

- *Average communications overhead on the UMTS uplink channel needed for the V2V connectivity context generation.* The instantaneous communications overhead (in bytes/s) generated on the UMTS PRACH by the compared uploading techniques is averaged over time windows of 60s. When RoAHD is adopted, this overhead is due to the uploaded *DCU* messages. When characterizing the connectivity based on connected sets of vehicles (Section 7.4), this overhead is due to the periodic upload of individual vehicle GPS positions. The time variation of this instantaneous overhead is analyzed to assess how the compared uploading schemes behave with increasing number of transmitting vehicles.
- *Average communications overhead on the ITS G5 control channel needed for the V2V connectivity context generation.* The instantaneous communications overhead (in bytes/s) produced on the ITS G5 control channel for the generation of the V2V connectivity characterization is averaged over time windows of 60s. Only RoAHD's V2V connectivity characterization requires generating overhead on the ITS G5 control channel. This overhead is due to the additional connectivity fields (*CFs*) and uploading fields (*UFs*) included in standard beacon messages by respectively DiRCoD and the *DCU* uploading schemes. This overhead is analyzed to quantify the ITS G5 channel cost that RoAHD's connectivity context generation requires compared to the other characterizations that do not need producing overhead in the VANET.
- *Total communications overhead on the UMTS uplink channel required for the implementation of the injection strategies:* represents the total communications overhead (in bytes) generated on the UMTS PRACH to implement the injection strategies described in Section 7.3.3 and Section 7.4. It is referred to as "total" as it considers the overhead generated along the entire simulated period. At the moment of executing a message injection, the TMC needs to know what vehicles are in the relevance area and hence are available to receive the injected message copies. For this purpose, besides the messages uploaded for the V2V connectivity context generation,

further uplink messages are needed. In particular, for the implementation of RoAHD's IBRCC and FPRCC injection strategies (Section 7.3.3.1), and the GPS and Random injection strategies (Section 7.4), it is considered that vehicles upload one message (of the same size of *DCUs*) every time they enter or leave the relevance area. These additional messages are not needed in the case of RoAHD's IBRCC-AP and FPRCC-AP (Section 7.3.3.2). In this case, vehicles inform the TMC about their availability to receive the injections. To do that, vehicles acknowledge their positions at road intersections using uplink messages of the same size of *DCUs*. For the Idealistic injection strategy, no overhead is considered.

- *Average Packet Delivery Ratio (PDR).* The PDR associated to the injection of the $\underline{n}$ available message copies is measured as the ratio between the vehicles receiving the message (directly from the UMTS node B or through TOPOCBB), and the total number of vehicles in the relevance area at that moment. The PDR values achieved by subsequent message injections along the entire simulated period are divided by the total number of injections to obtain an average value.

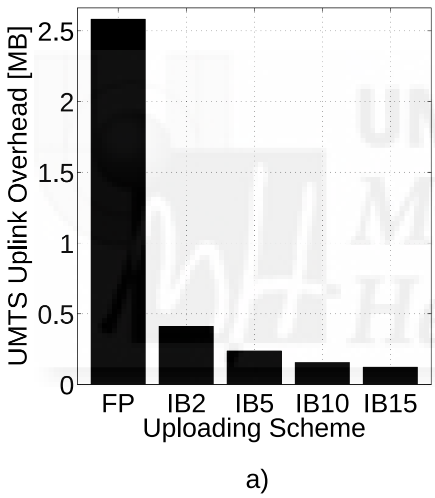
7.5.3 Results analysis

As introduced at the beginning of Section 7.5, the obtained simulation results are first analyzed concerning the effectiveness and efficiency of RoAHD's connectivity data collection mechanisms to support the generation of a global V2V connectivity context characterization. Later on, further simulation results are shown to demonstrate how RoAHD's message injection strategies exploit this context knowledge to achieve good levels of message delivery over the considered relevance area.

7.5.3.1 V2V connectivity context characterization

For this first analysis, the RoAHD's IB uploading scheme is assessed in its capability to generate a correct V2V connectivity context as a function of its uploading timer duration parameter T_U. For this purpose, it is compared with the reference FP scheme that, according its definition, is expected to provide a more precise characterization but at a higher channel cost. For this analysis, the vehicular traffic Scenario 2 defined in Section 7.5.1 is considered.

Figure 7-16 compares the total communications overhead required by IB to that needed by FP. "IBx" indicates the IB uploading scheme operating with an uploading timer duration T_U of x seconds. As defined in Section 7.3.1.2, the FP scheme uploads separate *DCU* messages for each DiRCoD connectivity fields *CFs* overheard by vehicles at road intersections. Since distinct *CFs* are overheard from adjacent road segments almost every *CF generation period* seconds (2s in this work), *DCU* messages are uploaded very frequently by this scheme. On the contrary, the IB scheme uploads *DCUs* that include all the *CFs* overheard by vehicles when crossing an intersection. The frequency of IB's *DCU* uploading is then controlled by the adopted T_U. As a result, the IB uploading scheme generates on the UMTS uplink channel an overhead up to 20 times smaller than FP scheme's overhead if a T_U of 15s is used (Figure 7-16a). A similar trend is observed in Figure 7-16b for the overhead generated on the ITS G5 control channel. Both the FP and IB schemes require extending standard beacons with an additional uploading field *UF* every time a new *DCU* is uploaded. Since the FP mechanism uploads many more *DCUs* than IB, it creates a higher ITS G5 overhead. However, since the additional *UFs* only require one byte information carried over standard beacon messages, the overhead generated by the uploading schemes in the VANET is much lower compared to that produced on the cellular uplink channel (FP generates on the ITS G5 channel a 50 times smaller overhead than that produced on the cellular uplink channel).



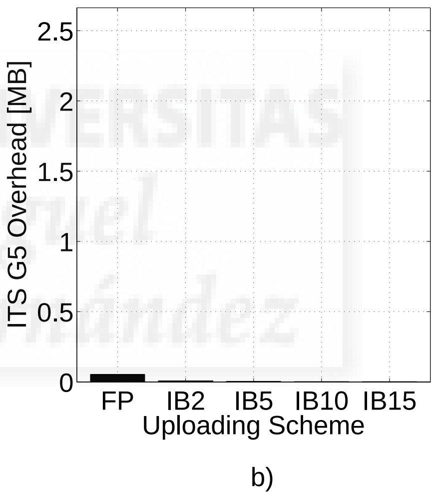


Figure 7-16. Total communications overhead on the UMTS uplink channel (a) and on the ITS G5 channel (b) needed for the generation of the V2V connectivity context (traffic Scenario 2).

Figure 7-16 has demonstrated that important channel savings over both the cellular and vehicular ad-hoc networks can be achieved collecting DiRCoD's road connectivity information with the IB scheme. In order to understand the effects of adopting this more channel efficient collection mechanism on the accuracy of the V2V connectivity context characterization, Figure 7-17 to Figure 7-20 depict the time variation of the coverage level estimation error $e_{CLij}(t)$ for a single road segment $I_i \rightarrow I_j$. As defined by equation (7-7), this error derives from the difference between the instantaneous CL_{ij} values obtained by applying respectively IB and FP, and reported in the upper graphs of the figures. Figures labelled with increasing numbers report results concerning IB uploading schemes using higher values of the uploading timer duration T_U. The road segment considered for this evaluation belongs to the zone 1 highlighted in Figure 7-15. Over this set of road segments, the experienced vehicular traffic density has the lowest observed value (3 vehicles/km/lane) in the first part of the simulation. In the central part, the vehicular density is more variable and has an increasing trend. The vehicular density reaches the maximum observed value (22 vehicles/km/lane) and remains stable until the end of the simulation. The effects of this vehicular density variation on the coverage level computation can be observed in the upper graph of Figure 7-17 taking into account the CL_{ij} estimated applying FP. As it can be observed, the road segment provides very poor and very good coverage levels respectively at the beginning and at the end of the simulation, as a consequence of respectively low and high vehicular density values. In the central part of the simulated time, the variability of the vehicular traffic results in less stable coverage level assessments. As it can be observed in the lower graph of Figure 7-17, IB with a 2s uploading timer duration T_U can almost perfectly estimate the coverage level of the road segment over the time periods characterized by stable high or low vehicular traffic density. In fact, over the first and last part of the simulated time, the estimation error $e_{CLij}(t)$ is very close to zero. On the contrary, the CL_{ij} estimation obtained with IB is less precise in conditions of variable traffic density. In the central part of the simulation, although the CL_{ij} calculated applying IB generally follows the trend of that obtained with FP, the estimation error $e_{CLij}(t)$ presents a few peaks higher than 0.5. This is due to the fact that IB is not as "fast" as FP in notifying the TMC about instantaneous changes of the road segment's multi-hop connectivity. As it can be expected, this capability is further compromised by adopting higher values of the uploading timer duration T_U.

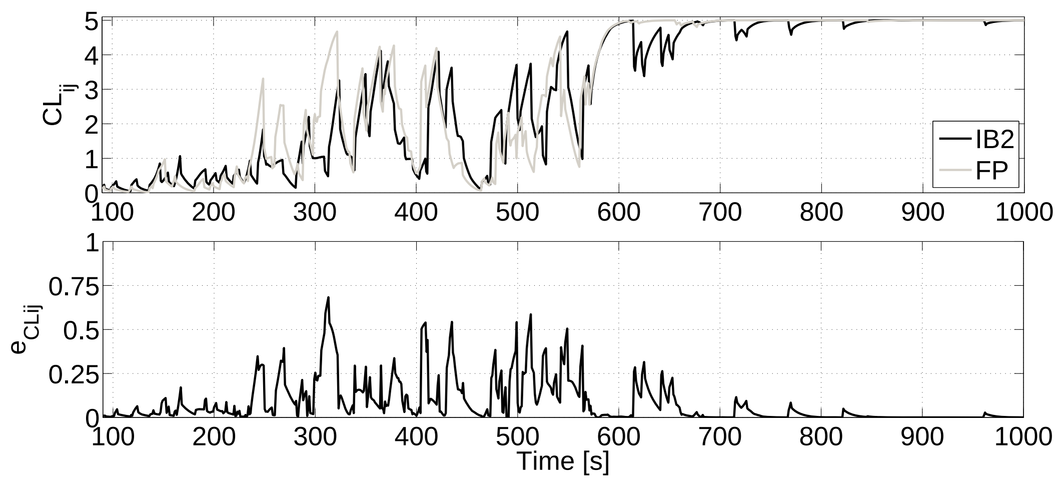


Figure 7-17. Time variation of the CL estimation error over a road segment Ii→Ij (IB with T_U=2s; traffic Scenario 2).

As demonstrated by figures 7-18 to 7-20, the estimation error generally increases as a function of T_U, and registers more non-negligible values even in time periods with stable vehicular density. In fact, by collecting *DCUs* less frequently, the TMC's connectivity processing scheme considers the received road connectivity assessments valid for longer periods, and ignores the actual connectivity changes that may occur in the meanwhile. As a consequence, it generates coverage level errors with higher probability.

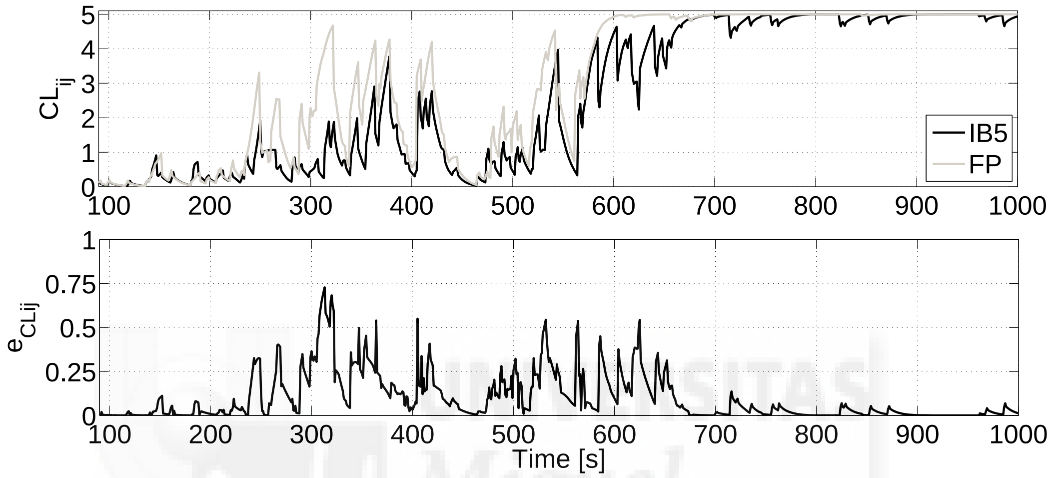


Figure 7-18. Time variation of the CL estimation error over a road segment $I_i \rightarrow I_j$ (IB with T_U=5s; traffic Scenario 2).

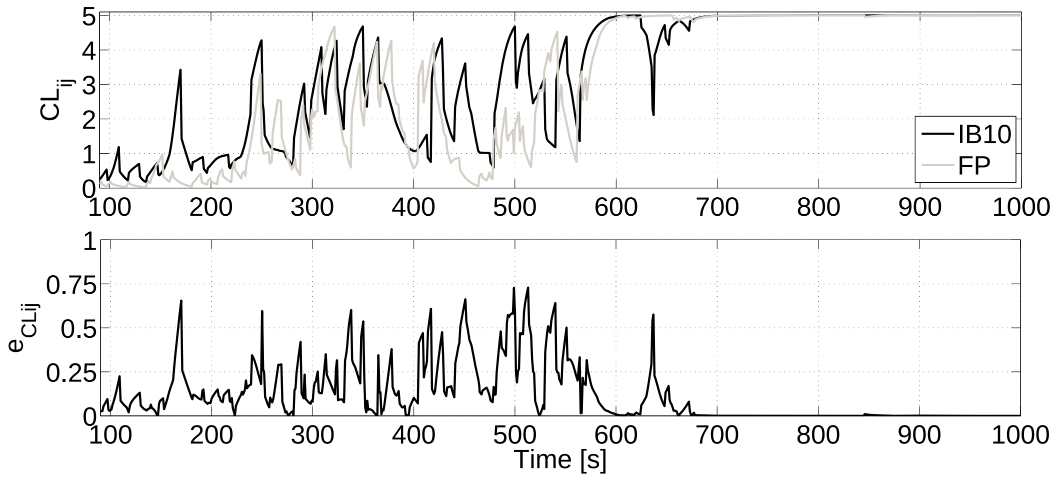


Figure 7-19. Time variation of the CL estimation error over a road segment $I_i \rightarrow I_j$ (IB with T_U=10s; traffic Scenario 2).

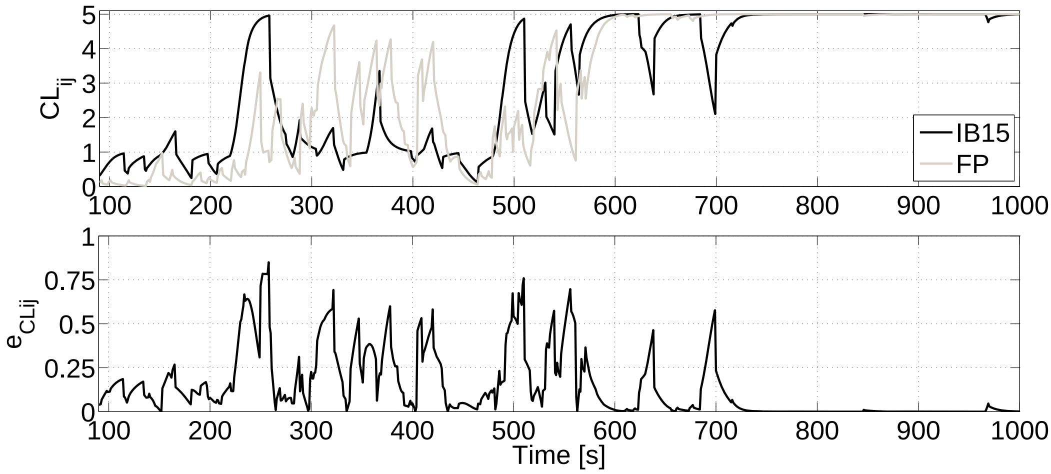


Figure 7-20. Time variation of the CL estimation error over a road segment $I_i \rightarrow I_j$ (IB with T_U=15s; traffic Scenario 2).

Figure 7-21 shows the time variation of the estimation error e_{CLij} spatially averaged over all the road segments of the considered road network as defined by equation (7-8). With this figure it is possible to analyze a larger scale characterization of how the V2V connectivity context estimation can be degraded by using IB with increasing values of T_U. The figure shows that IB can generate a satisfactory global V2V connectivity picture even using moderately high values of its uploading timer duration T_U. In fact, although an estimation degradation is visible for increasing values of T_U, this degradation almost never results in estimation errors higher than 0.2, even when IB adopts a T_U of 15s.

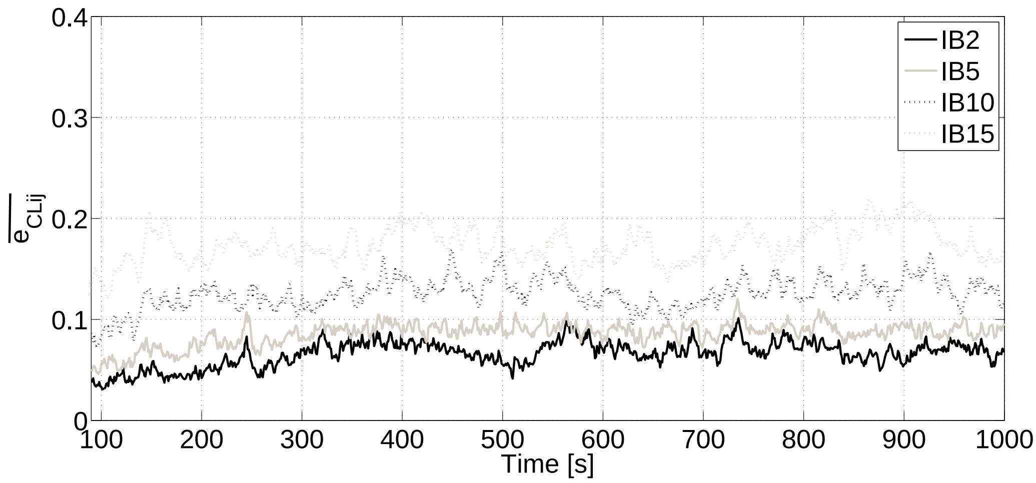


Figure 7-21. Time variation of the CL estimation error averaged over all the road segments of the road network (traffic Scenario 2).

Apart from calculating the estimation error, it is also important to measure the correlation between the V2V connectivity context characterizations. As explained in Section 7.5.3.1, the context characterization obtained by IB might not result as accurate as that that retrieved with FP. However, if the context characterization obtained by IB correlates well with the reference characterization, then it is expected to generate similar injection decisions and hence result in similar delivery performance. In this context, Figure 7-22 shows the time variation of the statistical correlation between the CL_{ij} values computed using IB and FP. The statistical correlation is calculated with the Pearson correlation coefficient defined by equation (7-10); good correlation is obtained for values of the correlation coefficient close to 1. The results show that the V2V connectivity context characterization obtained with IB is well correlated to that derived with FP when a relatively low T_U (up to 5s) is used. This property holds during the entire evaluation period, independently of the time and space vehicular density variations. Using higher T_U values implies a degradation of the correlation, although values higher than 0.75 are usually observed.

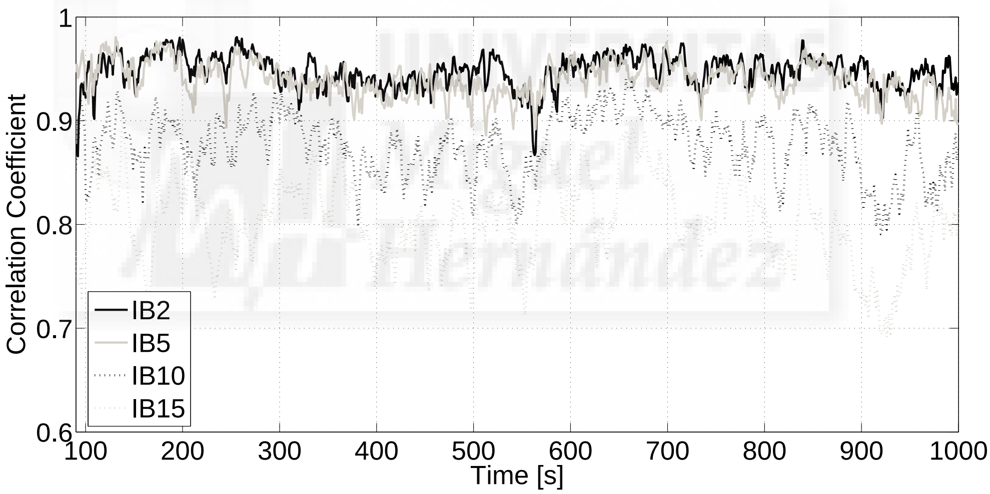


Figure 7-22. Time variation of the statistical correlation between CL_{ij} values obtained with IB and FP (traffic Scenario 2).

To conclude this analysis, Figure 7-23 and Figure 7-24 depict time averages of the estimation error and correlation coefficient reported respectively in Figure 7-21 and Figure 7-22. These time averages are calculated considering the entire simulated period. Figure 7-23a shows the estimation error e_{CLij} spatially averaged over all the road segments of the road network, and time averaged over subsequent time steps T of 1s (according to equation (7-9)). Figure 7-23b and Figure 7-23c depict analogous spatio-temporal averages, but only considering the estimation error over the sets of road segments indicated respectively with "zone 1" and "zone 2" in Figure 7-15. As previously mentioned, over the zone 1 the vehicular traffic density has lower values in the first part of the simulation, higher values in the last part, and intermediate variable values in the central part. The vehicular density over the zone 2 has variable values with an average of 12 vehicles/km/lane during the entire simulated period. As previously explained, the connectivity context characterization achieved applying IB is negatively influenced by variable traffic conditions. As a result, the average coverage level estimation error over zone 2 is higher than in other parts of the road network, e.g. zone 1. However, as it can be seen in Figure 7-23c, this error is contained under a relatively low value of 0.2, which demonstrates a good capability to locally assess the V2V connectivity even with the highest simulated T_U. Figure 7-23a confirms that considering the totality of road segments, the V2V connectivity context can be properly estimated using IB with a low uploading timer duration of 2s. With higher values of the simulated T_U, this capability deteriorates, but is not considerably compromised as the maximum observed error stays under 0.2.

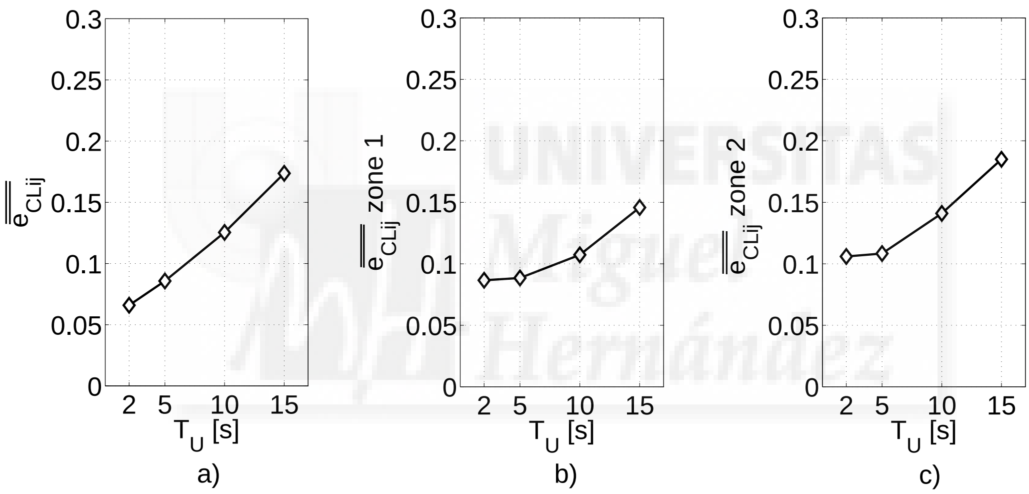


Figure 7-23. Spatio-temporal average of the CL estimation error as a function of IB's uploading timer duration T_U (traffic Scenario 2).

This conclusion is reinforced by Figure 7-24 that depicts the temporal average of the correlation coefficient defined by equation (7-11). This indicator measures the average correlation of the V2V connectivity context achieved by IB with that obtained using FP. As it can be observed, a good average correlation (always higher than 0.8) exists even with the highest simulated T_U. As it is shown in the following, injection strategy decisions based on such correlated road connectivity characterizations result in similar V2X dissemination performance.

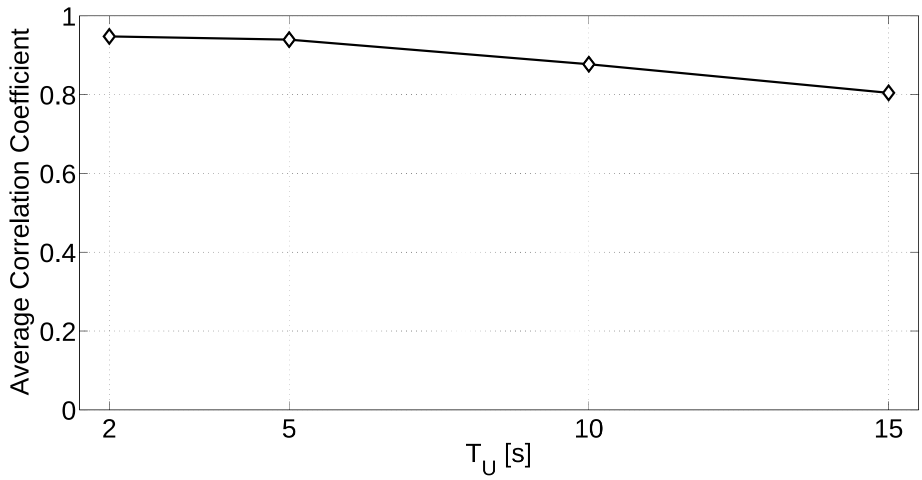


Figure 7-24. Temporal average of the statistical correlation between CL_{ij} values obtained with IB and FP as a function of IB's uploading timer duration T_U (traffic Scenario 2).

7.5.3.2 Message injection strategies

The simulation results shown in the previous section have demonstrated that a global V2V connectivity picture built on road connectivity information collected with IB is not significantly different from that achieved with FP. More interestingly, the two V2V connectivity context characterizations are relatively well correlated with each other. As it has been shown, the capability of IB to achieve this correlation decreases for higher values of T_U. However, as previously proven, using higher T_U implies lower cellular uplink channel costs, which might be relevant for the future implementation of cooperative ITS applications using cellular resources. In this context, this section shows simulation results to verify if the less accurate, but more channel efficient V2V connectivity characterizations achieved with IB can leverage the implementation of effective RoAHD's message injection strategies.

RoAHD's injection strategies defined in Section 7.3.3 are compared to the strategies that inject message copies over the largest connected sets of vehicles (CSVs) in the VANET (Section 7.4). To compute the size of CSV the TMC assumes that any two vehicles can communicate in the VANET if they are not driving on roads obstructed by buildings, and are separated by less than a distance *r*. Using distinct values of *r* results in CSVs of different size. This in turn influences the injection decisions and the resulting V2X delivery performance. To ensure that the injection strategies defined in Section 7.4 are able to obtain the best delivery performance, their effectiveness with different values of *r* has been tested. This evaluation has been made by simulating the Idealistic injection strategy in which the connectivity processing scheme is considered to know the actual position of every vehicle (see section 7.4) at each moment. The results shown in this section refer to a configuration in which n=5 message copies are injected and the vehicular traffic Scenario 2 is considered. Four different values of *r* have been tested. It is important to recall that, although the TMC computes the CSVs assuming that two vehicles separated by less than *r* can successfully communicate, this may not always be the case in the reality. The capability for two nodes to communicate at a given transmission power and distance *r* can only be described in probabilistic terms. Considering the iTETRIS' realistic V2V propagation model and the adopted 20dBm transmission power, the tested values of *r* correspond to the reception probabilities reported in Table 7-1. These probabilities can be inferred from Figure 5-9.

***r* [m]**	**Probability of successful V2V message exchange as a function of *r* [%]**
95	99
150	90
180	80
200	70

Table 7-1 Probability of successful V2V message exchange as a function of the inter-vehicular distance *r* (20dBm transmission power; WINNER B1 propagation model [147]).

The dissemination delivery performance achieved by the Idealistic strategy with a given value of *r* is measured by averaging the packet delivery ratio (PDR) obtained in the relevance area with injections of n messages. It is important recalling that store, carry and forward techniques are not considered in the V2V dissemination of the injected messages. Figure 7-25 shows that the Idealistic injection strategy obtains the highest average PDR, when it computes CSVs considering a value of *r* set to 150m. Computing the CSVs with higher values of *r* results in considering lower probabilities of inter-vehicle message exchange (Table 7-1). This might overestimate the actual connectivity properties of the calculated CSVs in some cases. Injecting in such CSVs starts to negatively affect the V2V dissemination of the messages injected in the VANET, which results in lower PDR values as depicted in the figure. The PDR associated to a value of *r* set to 95m is very close to that achieved with *r* set to 150m. As introduced in Section 7.5.1, 95m corresponds to the communications range considered by RoAHD for the implementation of the DiRCoD mechanism with a 20dBm transmission power (Table 5-1). In this context, taking into account the results of Figure 7-25, setting the parameter *r* to a value of 95m can be considered as a reasonable choice for the computation of CSVs.

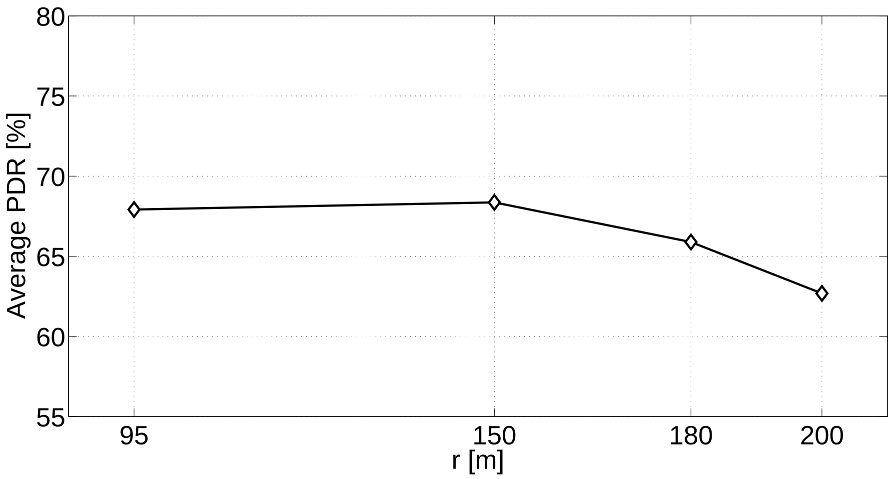


Figure 7-25. Average PDR as a function of the inter-vehicular distance *r* used for the computation of CSVs (5 injected messages; traffic Scenario 2).

The GPS injection strategy also injects message copies on the largest CSVs. However, differently from the Idealistic injection strategy, this strategy computes the CSVs based on the GPS positions that every vehicle uploads with a regular period of *p* seconds. Uploading GPS positions with low values of *p* results in computing CSVs that tend to be similar to those obtained by the idealistic strategy, and hence permits obtaining similar PDR results. However, it also requires a higher use of cellular uplink resources. To find an optimal compromise between accuracy of the context representation and cost of channel resources, the GPS injection strategy has been simulated with increasing values of the GPS uploading period *p*. The results are reported in Figure 7-26. The results are obtained injecting 5 message copies in the vehicular traffic Scenario 2. The inter-vehicular distance *r* used for the computation of CSVs is set to 95m following the above mentioned considerations. As it can be observed, if GPS positions are uploaded every 2s, the obtained average PDR is very similar to the maximum value obtained by the Idealistic injection strategy (Figure 7-25). This performance gradually decreases with higher values of the uploading period *p*. A good tradeoff between PDR and UMTS uplink overhead is registered for an uploading period of 10s. With this uploading period, the GPS injection strategy requires more than 5 times less overhead to achieve almost the maximum measured PDR. According to the obtained results, in the following performance comparisons the Idealistic and GPS injection strategies are always considered to compute CSVs using a value of *r* equal set to 95m. Moreover, the GPS injection strategy is considered to adopt a vehicle GPS positions uploading scheme with a period *p* of 10s.

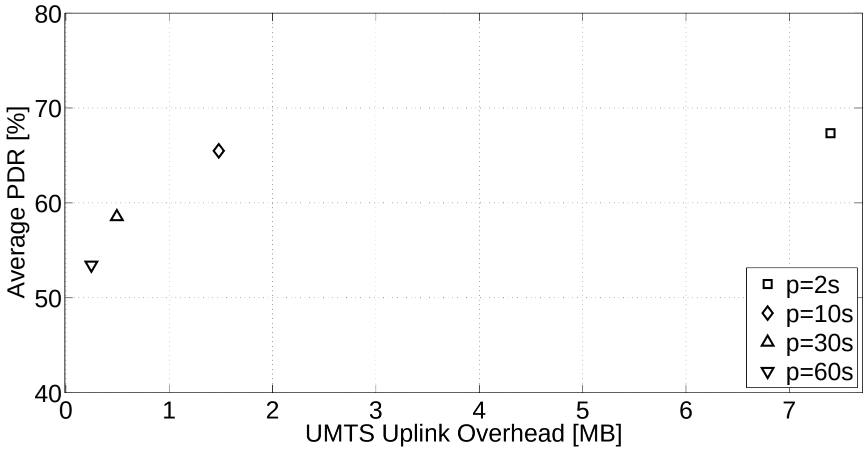


Figure 7-26. Average PDR as a function of the UMTS uplink overhead for various values of the GPS uploading period *p* (5 injected messages; traffic Scenario 2).

Figure 7-27 and Figure 7-28 compare the time variation of the average communications overhead generated by the vehicle position uploading scheme of the GPS injection strategy ("VP" in the figure) with that measured when applying RoAHD's IB and FP uploading schemes. The lower overhead generated by RoAHD's IB scheme compared to FP was already demonstrated in Figure 7-16. Figure 7-27 shows that IB is also more efficient than the VP uploading scheme, as it generates a UMTS uplink overhead up to 12 times smaller (when a T_U of 15s is considered) on average. Moreover, the overhead of both FP and VP is much more dependent on the total number of vehicles present in the road network compared to that generated by IB. In fact, their overhead fluctuates proportionally to the total number of vehicles in the scenario. Irrespectively of the total number of vehicles in the scenario, IB uploads *DCU* messages only at road intersections, and only when determined by the uploading timer. Consequently, IB requires less cellular uplink resources and offers better scalability perspectives for increasing values of the vehicular traffic. This property is more evident for higher values of T_U. To derive its connectivity context characterization, RoAHD requires the use of cellular and ITS G5 resources. The overhead within a VANET is due to the additional connectivity fields (*CFs*) and uploading fields (*UFs*) included in standard beacon messages respectively by DiRCoD, and the IB and FP schemes. However, the small overhead generated per *CF* and *UF* results in that RoAHD's VANET overhead is limited compared to that created on the UMTS uplink channel by VP (Figure 7-28). These results indicate then that RoAHD's IB uploading scheme can assist the generation of a global VANET's V2V connectivity characterization by balancing the necessary channel costs over the cellular and vehicular ad-hoc networks.

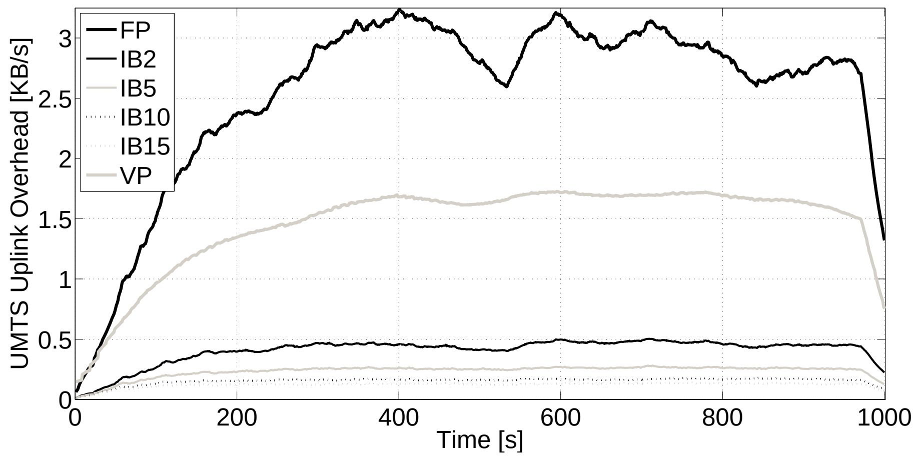


Figure 7-27. Time variation of the average communications overhead on the UMTS uplink channel (traffic Scenario 2).

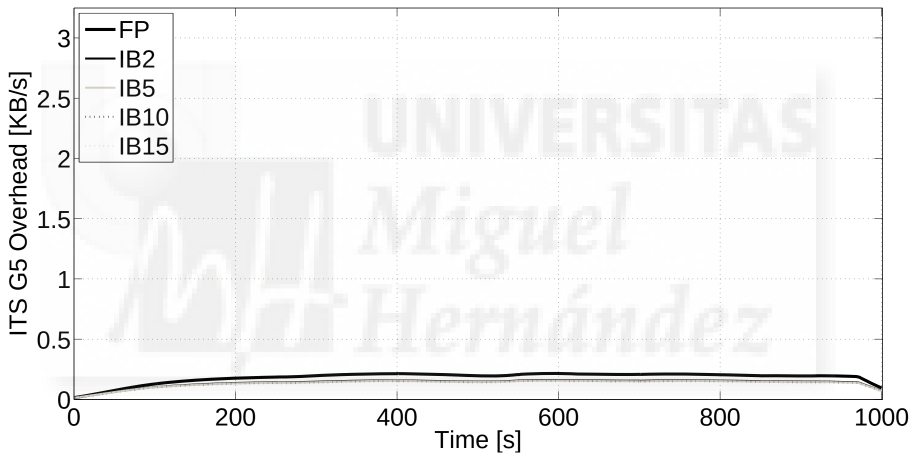


Figure 7-28. Time variation of the average communications overhead on the ITS G5 channel (traffic Scenario 2).

To demonstrate that RoAHD's channel efficient connectivity characterization can successfully support effective injection strategies, simulation results concerning the injection of 5 message copies in the vehicular traffic Scenario 2 are next presented. Figure 7-29 depicts, for each of the compared injection strategies, the obtained average PDR, along with the total UMTS uplink overhead required for its implementation. Different injection strategies are categorized according to the adopted V2V connectivity characterizations (see Section 7.3.3 and Section 7.4), with the exception of the "Random" injection strategy that does not use any connectivity context knowledge. The "GPS" and "Idealistic" injection strategies achieve a V2V connectivity context characterization considering respectively uploaded GPS and actual vehicle positions. RoAHD's injection strategies use a multi-hop road connectivity characterization obtained with the IB or FP uploading scheme. Accordingly, they are indicated respectively as “IBRCC” and “FPRCC” injection strategies. If the adopted IB uploading scheme uses an uploading timer duration of x seconds, the associated injection strategy is indicated with “IBRCCx”. “IBRCC-AP” and “FPRCC-AP” indicate RoaHD’s strategies requesting vehicles to acknowledge their presence at road intersections before executing message injections (Section 7.3.3.2). The obtained results show that, excluding the Idealistic injection strategy, the Random injection strategy requires the lowest channel cost to be implemented. The only cellular uplink transmissions adopted for this strategy are those through which vehicles notify the TMC when entering or leaving the relevance area. To this communications overhead, the other injection strategies sum the overhead needed to generate their V2V characterizations (Figure 7-27). The FPRCC-AP and IBRCC-AP strategies do not need that vehicles announce their entrance and exit through the relevance area, but require them to acknowledge their presence at intersections with cellular uplink transmissions. This permits FPRCC-AP and IBRCC-AP strategies to save a given percentage of overhead (up to 10% considering IBRCC-AP) compared to the basic IBRCC and FPRCC schemes.

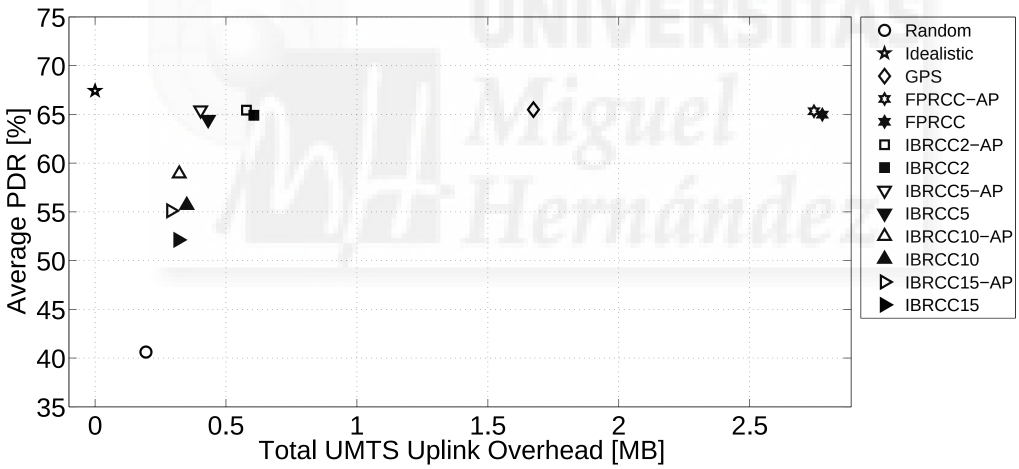


Figure 7-29. Average PDR vs. total communications overhead on the UMTS uplink channel (5 injected messages; traffic Scenario 2).

Although generating the lowest overhead, the Random injection strategy returns the lowest PDR. In fact, randomly selected injection vehicles may either be disconnected from other vehicles of the VANET, or belong to the same connected sets. As a result, they prevent an effective V2V dissemination of the message on the overall relevance area. On the contrary, the delivery performance of the GPS strategy (60% higher than that obtained by the Random strategy) indicates that the use of a V2V connectivity characterization helps the TMC to perform effective injection decisions. The fact that the

PDR obtained by the GPS strategy is very close to that achieved with the Idealistic strategy suggests that a relatively precise context characterization can be obtained even by uploading GPS positions not very frequently (every 10s in this case). However, this precision is paid by the GPS strategy at the expense of a UMTS uplink overhead that is significant compared to RoAHD's IBRCC strategies. RoAHD's context representation permits detecting sets of intersections and road segments over which the VANET can support reliable V2V dissemination of messages to the highest number of vehicles. The more frequently this characterization is updated, the better it supports effective injection decisions. In this context, RoAHD's FPRCC injection strategies return PDR values very close to those registered by the Idealistic strategy. However, the FP uploading scheme causes a very high channel cost (60% higher than that required by the GPS strategy). Differently from the FPRCC strategies, the IBRCC strategies update their context characterization with the more channel efficient IB uploading scheme. This permits saving higher amounts of cellular channel resources. As it can be seen in the figure, the higher efficiency of IBRCC strategies is not paid at the expense of delivery effectiveness, at least when adopting a T_U lower or equal than 5s. With this configuration, the IBRCC5 strategies can save up to 76% cellular overhead compared to the GPS injection scheme while providing almost the same PDR. This result proves that the context characterization achieved by the IB uploading can perfectly drive the implementation of RoAHD's injection strategies, and confirms with a practical implementation the study performed in Section 7.5.3.1. Figure 7-29 further shows that IBRCC-AP and FPRCC-AP generally provide higher PDR than the IBRCC and FPRCC injection schemes. However, this difference starts being significant only for IBRCC strategies based on a T_U higher or equal than 10s. Before injecting, the IBRCC-AP and FPRCC-AP strategies request vehicles at intersections to acknowledge their positions. This process allows ensuring that message copies are transmitted to vehicles placed close to the center of the intersections selected for the injection. On the contrary, the IBRCC and FPRCC schemes inject on the vehicles that last uploaded a *DCU* for these intersections. When *DCUs* are not uploaded very frequently, like in the case of IBRCC strategies based on a T_U higher or equal than 10s, these vehicles are more likely to be already far from the intersection centers. In the worst cases, they might be disconnected from the other vehicles in the addressed connected sets of intersections (CSIs), and hence might not always guarantee a reliable V2V dissemination in the VANET.

For values of T_U higher or equal than 10s, the IBRCC-AP and IBRCC schemes obtain lower PDR as a consequence of considering coarser multi-hop road connectivity context characterizations. In these cases, message copies are injected on CSIs that might not always be as connected as expected, or on intersections not actually providing the computed coverage levels. However, as explained in Section 7.3.3.3, the delivery performance could be improved in these scenarios using injection strategy variants aimed at performing centric or multiple injections over the selected CSIs. The effect of applying these optimization techniques to RoAHD's injection strategies is reported in Figure 7-30. Injecting message copies on the most centric intersections of the selected CSIs ("Centric" in the figure) ensures higher PDR values as it permits a more capillary V2V dissemination on average in reaction to possible CSI partitions. As expected, these PDR improvements are more evident for the strategies that are more likely to be affected by these disconnections (IBRCC and IBRCC-AP strategies with T_U higher or equal than 10s). Figure 7-30 demonstrates that further improvements can be achieved with multiple injections over the CSIs selected for the injection ("Multiple" in the figure). The results shown in this figure derive from applying a value s=5 in equation (7-6). In this way, differently from only injecting one message copy per CSI, the strategies inject as many additional copies in a CSI as its size equals multiples of 5 intersections. This choice is motivated by the fact that in the considered scenario, CSIs have a maximum observed size of 7 intersections. According to this, and following equation (7-6), a maximum number m=2 of message copies can be injected in the same CSI. It is important to recall that injecting an additional message copy over a CSI bigger than 5 intersections does not change the total number $\underline{n}$=5 of injected messages. As Figure 7-30 demonstrates, this variant increases the PDR given that multiple injections help the V2V dissemination to react against localized disconnections in CSIs of higher size. Again, the higher PDR improvements are obtained by the IBRCC and IBRCC-AP strategies with higher T_U, which demonstrates that the negative effects of considering a coarser connectivity context can be partially overcome by distributing the injections of message copies in a smarter way.

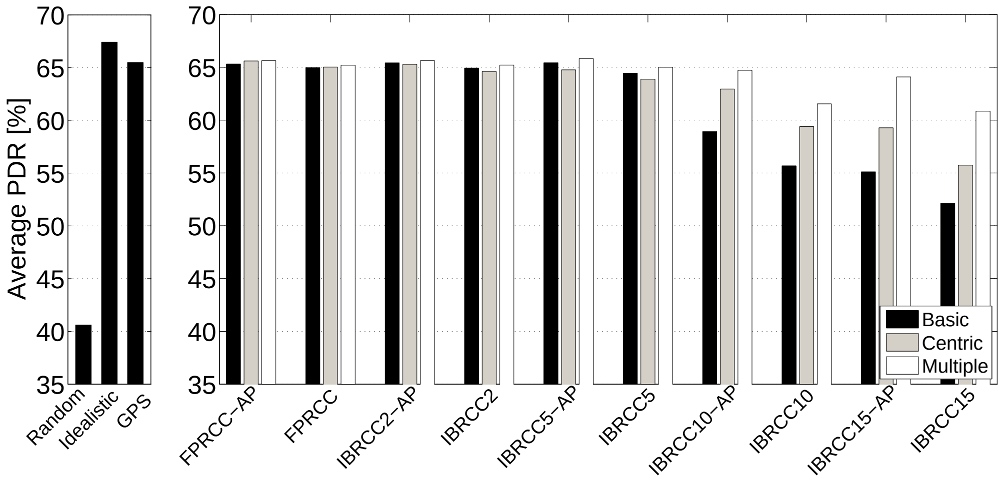


Figure 7-30. Average PDR of the basic injection strategies compared with that obtained using the centric and multiple injection strategy variants (5 injected messages; traffic Scenario 2).

Considering the results depicted in Figure 7-30 and Figure 2-1 and Figure 7-29, it is possible to conclude that RoAHD's IBRCC15 and IBRCC15-AP injection schemes provide the best tradeoff between V2X dissemination delivery effectiveness and channel efficiency. In fact, these strategies achieve a PDR very close to that obtained by the Idealistic injection strategy while generating almost the lowest cellular uplink overhead. Compared to the GPS injection strategy, this PDR is obtained with up to 82% less cellular uplink resources. In order to study how this performance varies for different operational conditions, Figure 7-31 compares the presented injection strategies as a function of the number $\underline{n}$ of injected message copies. As expected, injecting more copies in the VANET implies increased PDR over all the injection schemes. In addition, the superiority of the PDR achieved by injection strategies considering a context characterization compared to the PDR obtained by the Random strategy is more evident when less message copies are injected. This indicates that considering context knowledge is particularly useful when V2X dissemination delivery performance wants to be achieved with a limited number of downlink injections. As previously demonstrated, this context knowledge can be obtained using RoAHD's IBRCC15 strategies with a very limited channel cost compared to all the other analyzed strategies.

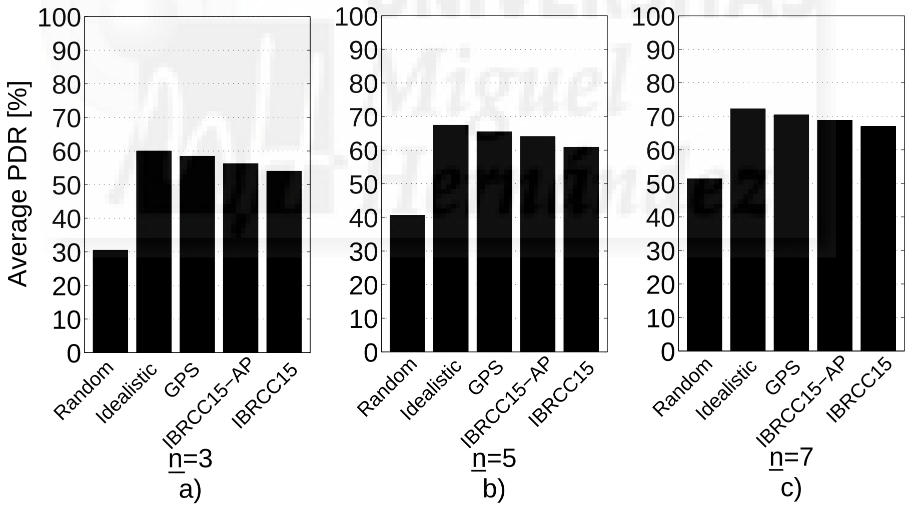


Figure 7-31. Average PDR as a function of the number $\underline{n}$ of injected message copies (traffic Scenario 2).

To conclude this study, Figure 7-32 compares the delivery and channel efficiency performance of the injection strategies for varying vehicular traffic scenarios. For this analysis, the considered number $\underline{n}$ of injected message copies is set to 5. As explained in Section 7.5.1, traffic scenarios labelled with increasing numbers represent situations with increasing vehicular densities. Higher vehicular densities automatically generate better V2V connectivity conditions in the VANET. Moreover, with a higher presence of vehicles, the CSVs and CSIs selected respectively by the GPS and Idealistic, and by

RoAHD's IBRCC15 strategies, contain more recipient vehicles. As a result, the achievable PDR increases with the vehicular density. Compared to the Random injection scheme, these injection strategies are more effective for lower vehicular densities, as the superiority of the obtained PDR is higher in such conditions (Figure 7-32a). This indicates that considering context information for V2X dissemination is more helpful as the overall VANET's connectivity decreases. Considering the total overhead needed for the implementation of the compared schemes, Figure 7-32 confirms the better efficiency of RoAHD's injection strategies compared to the GPS injection scheme. This efficiency increases for scenarios with higher density of vehicles (in Figure 7-32c the IBRCC15 strategies generate up to 86% less uplink overhead). In fact, the GPS strategy builds the connectivity context by processing individually uploaded vehicles positions. In this case, the higher the number of transmitting vehicles, the higher the generated uplink overhead. On the contrary, RoAHD's overhead is less dependent on the number of vehicles in the scenario. This overhead mainly depends on the number of intersections in the relevance area and the parameter T_U regulating the uploading period of the road connectivity information.

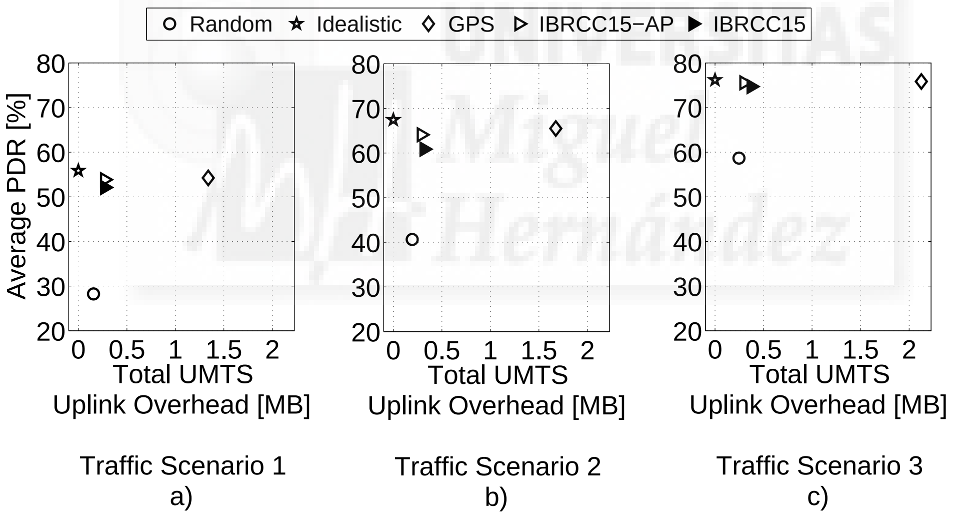


Figure 7-32. Average PDR vs. total communications overhead on the UMTS uplink channel for the three simulated traffic scenarios (5 injected messages).

7.6 Summary and discussion

This chapter has presented RoAHD, a complete framework for the dissemination of information through hybrid V2X communication systems. RoAHD combines the extended coverage capabilities of cellular systems and the multi-hop communications potential of vehicular ad-hoc networks. As argued, this integration permits to overcome the inefficiencies that could rise from the isolated use of one of these two technologies.

The information to disseminate is initially held by a centralized TMC. This information is replicated in a limited number of messages copies that are injected through the cellular system to specific vehicles belonging to the vehicular ad-hoc network. These message injections are followed by a cooperative V2V dissemination exploiting multi-hop broadcast transmissions at road intersections. To ensure that the injected message copies are delivered to highest possible number of vehicles, RoAHD's injection decisions make use of context information representing the capability of the VANET to effectively support the V2V dissemination. For this purpose, RoAHD defines and adopts a novel global V2V context characterization approach that looks into the multi-hop connectivity properties of road segments. The multi-hop connectivity information of road segments is measured in the VANET through distributed DiRCoD mechanism, and then uploaded to the TMC by efficient uploading techniques. At the TMC, this information is processed and fused in such a way to achieve a more generic connectivity map of the considered area. By centrally analyzing this global connectivity picture, the TMC implements RoAHD's message injection strategies aimed at smartly selecting the most appropriate vehicles in the VANET to start an effective V2V dissemination.

Simulation results have demonstrated that the adoption of information about the connectivity of road segments permits RoAHD to achieve a global context characterization with much less cellular overhead than traditional approaches based on uploaded vehicle GPS positions. The communications overhead generated by RoAHD is almost independent from the total number of vehicles in the considered scenario, which makes RoAHD more scalable in the consumption of cellular resources. Although RoAHD's estimation of the multi-hop road connectivity requires generating overhead also in the VANET, this overhead is very limited if compared to that produced over the cellular system. The multi-hop road connectivity context characterization was demonstrated to be an effective means to drive injection strategies. The dissemination delivery performance achieved by RoAHD's strategies is in fact very similar to that obtained by a benchmark strategy that performs optimal injection decisions thanks to an idealistic knowledge of vehicle positions. More interestingly, it was shown that RoAHD's injection strategies can be improved by variants aimed at reacting against possible local VANET disconnections. In this way, RoAHD's injection schemes can maintain almost optimal delivery performance even when working with coarser but less channel consuming V2V connectivity context characterizations. RoAHD's strategies have been also compared against a random injection strategy that does not use any context characterization. Compared to random injections, the superiority of RoAHD's strategies increases in situations of lower vehicular density, and when a reduced number message copies are injected. These achievements highlight the importance of considering V2V connectivity context information in such cases.

8

Conclusions and Future Work

Cooperative ITS systems are expected to bring a major change in road mobility thanks to the provision of advanced road safety and traffic management applications. Through the ubiquitous V2V and V2I exchange of information, these applications will allow detecting road hazards and problematic traffic situations with a useful advance. Informing distant vehicles about these risks or problems will permit drivers to react accordingly, thereby improving the overall road safety and efficiency. However, the successful deployment of cooperative ITS systems requires addressing various technical, organizational, economical and legal issues. From a technical point of view, the deployment of cooperative ITS systems is challenged by the strict requirements of cooperative applications, and by the adverse vehicular communication characteristics. For most cooperative applications, these challenges cannot be addressed by already deployed wireless technologies. As a result, international efforts led to developing the IEEE 802.11p/ETSI ITS G5 standards for vehicular communications. These standards allow direct transmissions between vehicles that can directly communicate with each other, as well as multi-hop transmissions between nodes that are out of their respective transmission ranges. Multi-hop transmissions are necessary for a number of cooperative ITS applications aimed at transferring messages to distant nodes or areas. They can also be used to distribute messages to a set of recipient vehicles over a relevance area. However, the effectiveness and efficiency of cooperative applications using multi-hop transmissions strongly depend on the adopted routing and dissemination protocols. The increased vehicular mobility, the difficult propagation conditions, the scarcity of radio resources, and the scalability requirements pose important challenges to the design of these mechanisms. In this context, this thesis has presented and evaluated novel vehicular routing and dissemination protocols based on the concept of multi-hop road connectivity. Real time estimates of the multi-hop road connectivity can be measured in the VANET in a very channel efficient way. A wise use of these estimates permits the presented routing and dissemination schemes to face the challenges posed by vehicular communication environments.

For each of the topics investigated in the thesis, the rest of this chapter reports the main conclusions and highlights the aspects that will require further study.

8.1 Evaluation environment

The complexity and large scale nature of the vehicular routing and dissemination protocols presented in this thesis has required evaluations through computer simulations. In general, simulations provide the necessary tradeoff between modelling accuracy, scalability, and repeatability of evaluations. Moreover, they provide increased flexibility in the generation of different evaluation scenarios. In this context, the author of this thesis contributed to the design and development of the open source iTETRIS simulation platform. As described in the thesis, iTETRIS integrates the ns-3 network simulator, the SUMO traffic simulator, and the implementation of cooperative ITS applications (iAPP) in a very modular way. Through this integration, iTETRIS can effectively emulate the mutual dependence between vehicular mobility, wireless communications, and cooperative ITS applications. The accuracy of the adopted vehicular mobility and wireless models permits iTETRIS to return reliable simulation results. The thesis has highlighted the important advances provided by iTETRIS in the field of cooperative ITS simulation. iTETRIS provides open interfaces to abstract application developers from the internal implementation of both traffic and wireless simulators. This solution permit cooperative ITS applications to be implemented and evaluated in iTETRIS in a modular and programming language-agnostic way. In addition, iTETRIS allows extending the capabilities of its open source wireless and traffic simulators separately and independently. This capability is enabled by the iCS middleware and its open interfaces. A very distinguishing feature of iTETRIS is the implementation of a communications modelling compliant with the ETSI standards for Intelligent Transport Systems Communications. This property is very important in the context of this thesis, as it has allowed implementing and testing the proposed protocols using standard compliant communication functionalities. Accurately modelling standard compliant cooperative ITS systems does not affect iTETRIS' capability to support large scale simulations. iTETRIS' large scale simulation potential is another remarkable feature that is enabled through intelligent design, modelling and implementation choices. It is worth highlighting that iTETRIS' open source characteristics also allow modifying the modelling accuracy based on the study objectives and constraints. This is particularly relevant for the wireless physical layer modelling, as it significantly influences the simulation execution time.

iTETRIS has been initially developed to evaluate cooperative ITS traffic management applications. As explained in Section 4.3.4, iTETRIS divides the period to simulate into simulation time steps of one second. The different iTETRIS blocks are sequentially triggered to simulate all the application, vehicular mobility or wireless communication events scheduled for a given time step. This implies that the iTETRIS integrated simulations cannot interact over time scales shorter than one second. For example, let us imagine that a cooperative application wants to activate the transmission of a wireless message m_2 directly after receiving a message m_1. In iTETRIS, the ns-3 simulation of m_1 transmission would be simulated in the time step t_1. By receiving from ns-3 the notification of m_1 reception, the application emulated in the iAPP would schedule the wireless simulation of m_2. However, this new ns-3 simulation would not be executed before the start of time step t_2. This simulation resolution limitation would generally not be critical for the evaluation of cooperative ITS traffic management applications. However, it might affect the precision of safety applications' testing. Therefore, future work will investigate the capability of iTETRIS to correctly enable simulations of safety applications with simulation time steps of shorter duration.

Further work will be also needed to update the implementation of the iTETRIS communication modules according to the evolution of ETSI ITSC specifications. Several of these specifications are still being defined at ETSI level. At the moment of writing this thesis, relevant discussion topics concern management layer functionalities for vehicular decentralized congestion control and multi-channel operation. Standardization discussions are also ongoing for the definition of security mechanisms, and for a better specification of some of the ITSC Facilities.

8.2 Multi-hop road connectivity characterization

Recent studies on vehicular routing have proposed dynamic approaches to adapt geographical forwarding paths to the actual connectivity status of the VANET. These protocols route messages over subsequent road segments showing a good capability to support reliable multi-hop transmissions. This approach has been shown in the literature to improve the performance of traditional vehicular routing. To correctly drive dynamic forwarding path selections, these protocols usually adopt methods to compute in real time the multi-hop forwarding capability of entire road segments. Various methods in the literature accomplish this task by assessing the vehicular density. These approaches are based on the assumption that a high number of vehicles on a road automatically implies reliable forwarding capability. However, to assess road vehicular density in a distributed way, these approaches require using additional and dedicated transmissions. This can result in non-negligible communications overhead that may negatively affect the operation of concurrent vehicular communications. Moreover, vehicular routing protocols selecting routes based on vehicular density may continuously forward messages on the densest roads, and therefore increase the risk of channel congestion over them. To overcome these limitations, this thesis has introduced the concept of "multi-hop road connectivity". Multi-hop road connectivity has been defined as the capability of a road segment to reliably support multi-hop transmissions independently on the vehicular density. The thesis has presented DiRCoD, a distributed and lightweight mechanism through which vehicles can estimate the multi-hop road connectivity in real time and by only using standard beacon messages. DiRCoD is designed to be aligned to current vehicular communication standards. The performance of DiRCoD has been evaluated through simulations against a state of the art mechanism assessing road density. The simulation results have clearly shown that DiRCoD's design solutions permit generating precise and frequent road connectivity updates with a very limited consumption of channel resources. This encourages the adoption of DiRCoD for the design of advanced vehicular routing and dissemination techniques based on multi-hop road connectivity awareness.

The design and operation of DiRCoD can be further improved. In its performance evaluation, DiRCoD has been assessed assuming that all vehicles communicate with the same transmission power. However, individual cooperative applications requirements and channel congestion control policies could force each vehicle to use a distinct transmission power. Using different transmission powers at vehicles placed in different sections of a road segment might affect DiRCoD's functioning. As explained in Section 5.2.2 (Figure 5-2a), the multi-hop connectivity of a road segment in the direction $I_1 \rightarrow I_2$ is estimated at intersection I_1 by forwarding DiRCoD connectivity fields in the opposite direction ($I_2 \rightarrow I_1$). Let us suppose that a DiRCoD connectivity field is forwarded by vehicle F with a higher transmission power than other vehicles, like for example B. When receiving the connectivity field at I_1, vehicle E would consider the road segment connected in the direction $I_1 \rightarrow I_2$. However, this estimation would not account for the lower transmission power of vehicle B, and its possible inability to forward a message to vehicle F. The impact of these situations to routing and dissemination protocols relaying on DiRCoD's assessments would require a careful investigation. The implementation of DiRCoD would benefit from protocol modifications to react to such occurrences. For example, a viable solution could be integrating information about the adopted transmission power in the forwarded DiRCoD connectivity fields (a similar approach is defined in [62]). In this way, vehicles would be informed about the transmission power needed to forward a message in a specific direction. They could decide whether to use this power according to the application's requirements and the currently experienced channel load. A vehicle can inform its neighbours about the adopted transmission power by including this information in its packets. Standardization activities are currently discussing on whether including the transmission power information in an optional header at MAC or Network level [171][172].

It could be also interesting to enrich the DiRCoD protocol with functionalities to generate advanced road connectivity assessments. In the current version, DiRCoD is able to return the multi-hop connectivity of the road segments adjacent to a given intersection. Solutions could be studied to retrieve indications about the connectivity of more distant road segments. Such indications would permit routing and dissemination protocols to improve their performance. Moreover, the current version of DiRCoD intentionally disregards measuring road segments' density, as it would require additional complexity and overhead. However, DiRCoD extensions could be investigated to understand whether it would be possible to obtain approximate road density estimates without requiring considerable additional overheads. These estimates could be used to distinguish multi-hop connected road segments based on the experienced density. Through such measure, routing protocols would be able to intentionally avoid the densest road segments to better prevent channel congestions over them.

It is important to recall that the evaluation of DiRCoD, as well as those of the routing and dissemination protocol using its estimates, has been performed in Manhattan-like road network scenarios. As argued in Section 5.5, this choice was simply aimed at easing the implementation of the DiRCoD mechanism. However, Section 5.2 discussed to applicability of DiRCoD in more generic road topologies. The evaluation of DiRCoD with road maps and vehicular traffic patterns resulting from real-world scenarios has been left to future work. A similar evaluation has been reserved for the vehicular routing and dissemination protocols based on DiRCoD operation.

8.3 Contention-based forwarding with multi-hop connectivity awareness

Based on the study on the multi-hop road connectivity characterization, this thesis has presented TOPOCBF, a novel vehicular GeoRouting proposal. TOPOCBF forwards messages through a contention-based scheme using broadcast transmissions. TOPOCBF's contention-based approach is designed to restrict broadcast transmissions over subsequent road segments that are selected during the forwarding process. Along the path to the final destination, messages are iteratively addressed to intermediate road intersections. At road intersections, forwarding vehicles "sense" the multi-hop connectivity of adjacent road segments estimated through the DiRCoD mechanism. By analyzing this information, vehicles choose the next target intersection to approach the final destination through reliable multi-hop transmissions. In this way, TOPOCBF's geographical forwarding paths get dynamically adapted to the current connectivity status of the VANET. TOPOCBF approach is aimed at overcoming the limitations of state of the art vehicular routing. Recent proposals also adopt dynamic selection of geographical forwarding paths. However, they base this selection on the roads' traffic density. To compute vehicular density in the VANET, they generate considerable communications overhead. Moreover, most of the proposed routing techniques adopt sender-based forwarding schemes that may result in transmitting over unreliable links and affect delivery effectiveness. To demonstrate how TOPOCBF overcomes these problems, simulations have been conducted using varying communication parameters and environmental conditions. The obtained results have demonstrated that the adoption of real time connectivity estimates and reliable contention-based transmissions permit TOPOCBF to achieve better delivery performance. Moreover, though the use of lightweight DiRCoD information, TOPOCBF can save important amounts of channel resources. More interestingly, TOPOCBF is able to distribute the communications load over the road network more uniformly, and thereby reduces the spatial probability of channel congestion. Compared to routing schemes adopting sender-based forwarding, these benefits are achieved at the expense of slightly increased latencies. However, TOPOCBF's latencies are acceptable for the majority of cooperative ITS applications requiring multi-hop communications.

TOPOCBF has been designed with the clear intention to evaluate the benefits of considering real-time multi-hop road connectivity estimates. For this reason, TOPOCBF does not initially consider recovery strategies aimed at maintaining the message forwarding active in conditions of connectivity absence. Investigating how TOPOCBF could benefit from the implementation of recovery strategies provides wide margin for future work. In this context, a possible recovery solution could be the use of store, carry and forward mechanisms. These mechanisms would temporarily suspend the multi-hop forwarding of messages, and exploit vehicular mobility to look for forwarding opportunities at later instants. Another interesting recovery strategy to investigate could be relaying messages over other radio access technologies. For example, a vehicle detecting a connectivity hole could check the feasibility to forward the message through cellular networks. In this case, appropriate mechanisms would be needed to correctly manage message routing over heterogeneous communication networks. Besides this, radio resource management policies should be specified to regulate the use of systems (in this case cellular networks) not initially dedicated to rely messages between distinct portions of a vehicular network.

Besides recovery strategies, the operation of TOPOCBF would be further improved by the presence of RSUs in the routing scenario. Thanks to their increased antenna height, RSUs benefit from better propagation conditions and generally allow wider-range communications [155]. Moreover, RSUs placed in different points of a road network could be interconnected by backbone links. These backbone connections would allow transferring messages to distant areas more reliably compared to wireless communications in the VANET [160]. To exploit these properties, TOPOCBF could integrate the knowledge of RSUs' geographical placement in its dynamic forwarding path calculations. The integration of these mechanisms would require investigations to quantify the prospective benefits in terms of delivery capability and channel load savings.

In addition, TOPOCBF's operation would take advantage from an improved version of DiRCoD as foreseen in the previous section. DiRCoD extensions providing connectivity measures of distant road segments would better prevent that routed message get blocked in connectivity holes. Moreover, if DiRCoD could return indications about the vehicular density of candidate road segments, TOPOCBF could intentionally forward messages over roads less prone to experience channel congestion.

Future implementations of vehicular routing protocols like TOPOCBF will have to adapt to standard specifications regulating the use of vehicular radio channels [172]. Following these specifications, multi-hop transmissions will be allowed on different channels based on the experienced communications load. As a consequence, mechanisms to adequately administrate TOPOCBF multi-hop transmissions over multiple channels will require a careful investigation.

8.4 Connectivity-aware hybrid V2X dissemination

The multi-hop road connectivity characterization has also been adopted in RoAHD, a vehicular data dissemination system using hybrid V2X communications. RoAHD implements a complete framework jointly exploiting the wider coverage capabilities of cellular networks and the multi-hop communication characteristics of VANETs. RoAHD's objective is disseminating traffic messages from a Traffic Management Center to the highest possible number of vehicles in a relevance area. Only using individual cellular transmissions could imply high traffic and energy costs to network operators. Disseminating solely through cooperative V2V transmissions in the VANET might not be reliable against network disconnections. To solve these issues, RoAHD defines a dissemination scheme running two subsequent steps. For each message to disseminate, the TMC injects a few copies to specific vehicles using cellular transmissions. Upon receiving the injected message copies, these vehicles start a cooperative V2V dissemination in the VANET. For this second step, RoAHD uses multi-hop broadcast transmissions through vehicles placed at road intersections. To ensure an adequate delivery of injected messages in the relevance area, RoAHD's injections are guided by context knowledge. This context information represents VANET's ability to support V2V dissemination. To obtain this knowledge, RoAHD adopts a V2V context characterization based on multi-hop road connectivity estimates. After retrieving context information using DiRCoD, vehicles upload multi-hop road connectivity estimates to the TMC. At the TMC, the connectivity information of all the road segments is processed and fused to generate a global connectivity map of the considered area. By analyzing this map, the TMC executes injection strategies aimed at injecting messages on vehicles that can start an effective V2V dissemination in the VANET.

Simulation results have demonstrated that RoAHD obtains a VANET's connectivity context characterization with much less cellular channel resources than other approaches. This better performance derives from uploading lightweight DiRCoD's multi-hop road connectivity information with a smart collection mechanism. RoAHD's cellular communications overhead is almost independent on the total number of vehicles in the considered scenario. Therefore, RoAHD offers better scalability in the use of cellular resources. Although the use of DiRCoD requires additional channel load in the VANET, this load is much lower than that produced over the cellular system. Simulation results have also proven that RoAHD's channel efficient context characterization properly supports the implementation injection strategies. Through these strategies, RoAHD obtains delivery performance almost matching that obtained by an idealistic strategy aware of actual vehicle positions at every instant. The thesis has also defined variants of RoAHD's injection strategies aimed at better reacting against possible VANET disconnections. It has been shown that these variants can further improve RoAHD's channel performance and delivery capability. RoAHD's superiority compared to random injection strategies increases in situations of lower vehicular density. A similar behavior is observed by fixing the vehicular density and decreasing the number of injected message copies. These results have demonstrated the importance of considering context information in such cases.

The V2V dissemination scheme adopted in RoAHD intentionally excludes the use of store, carry and forward techniques. This design choice was aimed at highlighting the ability of context characterizations based on multi-hop road connectivity to correctly support the implementation of injection strategies. The integration of store, carry and forward techniques in the overall RoAHD framework has been reserved to future work.

These techniques would permit vehicles that do not initially receive injected messages via multi-hop broadcast transmissions to be reached at later instants. RoAHD extension with store, carry and forward techniques would enable the investigation of new injection strategies. For example, injection strategies could be studied to guarantee contained reception latencies to vehicles that receive messages via store, carry and forward transmissions. Also, injection strategies that prioritize message delivery and reception latency in specific zones of the relevance area could be investigated.

Another aspect that deserves further investigation is the addition of RSUs in RoAHD V2X dissemination system. RSUs would not only improve the performance of the cooperative V2V dissemination in the VANET, but also permit implementing enhanced collection and injection mechanisms. Under the hypothesis of RSUs deployed in the relevance area and backbone connected to the TMC, vehicles could upload their multi-hop road connectivity estimates also using RSUs. Vehicles could perform these uploads when in direct connection with RSUs. Alternatively, vehicles could implement techniques to store their road connectivity estimates and upload them opportunistically upon reaching a RSU. Management policies could be studied to adequately distribute road connectivity uploading through RSU and cellular access. These policies would be aimed at generating a reliable and up-to-date VANET's context characterization while optimally administrating the communication resources. Backbone connections to RSUs could also permit the TMC to inject message copies in the VANET without always requiring cellular transmissions. In this case, strategies optimally combining cellular and RSU injections would require investigation.

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